REVIVAL OF WIND ENERGY APPLICATION IN SHIP PROPULSION WITH IMPLICATIONS FOR INDIAN SHIPPING : REVIEW AND RECOMMENDATIONS

By

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CERTIFICATE

It is certified that the work contained in the thesis entitled "REVIVAL OF WIND ENERGY APPLICATION IN SHIP PROPULSION WITH IMPLICATIONS FOR INDIAN SHIPPING : REVIEW & RECOMMENDATIONS ", by Debasis Dey, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

Due to recent energy crisis,renewable sources of energy are being sought.Wind energy has long been thought of as a renewable source of energy.Wind assisted sail power can be used in ship propulsion as an auxiliary energy source in order to reduce fuel consumption. One of the objectives of this thesis work is to study Wind Assisted Ship Propulsion for Indian Shipping.Therefore as a first of the thesis work, a review of research in this area is presented by bringing together diverse informations from aerodynamics,ship science and meteorology.Various sail types have been assessed and the manually controlled cat rig is recommended for a developing country like India.Estimated fuel saving due to sail assist in Indian coastal shipping is 10 % and Indian overseas shipping is 20 % of the present consumption,on the basis of available maritime statistics.The possibility of considerable saving in fuel and foreign exchange against a small capital investment is pointed out.

The second part of this thesis deals with experiments carried out on double membrane sail aerofoil which is considered more efficient than conventional single membrane sail.The aerofoil was formed by wrapping a nylon fabric over a circular pipe as leading edge and bringing the ends of the fabric to meet over a cusped trailing edge . The trailing edge chould rotate freely without any additional friction.The relative distance between the leading edge and the trailing edge was changed to give the fabric different tensions. Lift and drag coefficients for the sail aerofoil were obtained for three different chord lengths,each with three different Reynolds numbers.The test results are analyzed with respect to the data of previous research work carried out in this area . Suggestions for the future work are made at the end.

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NOMENCLATURE

c = chord length of airfoil

C_D = drag coefficient = $D/\frac{1}{2}\rho V^2 S$

C_{D_0} = drag coefficient at zero degree angle of attack

C_L = lift coefficient = $L/\frac{1}{2}\rho V^2 S$

D = drag on airfoil

L = lift on airfoil

Re = Reynolds number = Uc/ν

S = projected area of airfoil

U = free stream velocity

V = velocity of apparent wind

α = angle of attack

ν = kinematic viscosity

ρ = free stream velocity

CHAPTER 1

INTRODUCTION

In recent years,attempts are made to search new and renewable sources of energy.This is because all conventional sources of energy like coal,oil etc are exhaustible.Also the increasing demand and galloping prices of fuel have led to a fuel crisis.So in order to overcome energy crisis ,renewable sources of energy must be sought . Wind energy has long been thought of as a renewable source of energy . Wind energy is commonly used for generation of electricity by wind turbines. But one very good use of wind energy is in propelling ships by installing sail-rigs which will lead to fuel saving in the main propulsion unit(desiel engine).Moreover in the sea wind tends to be much stronger than on land and wind power being proportional to the cube of wind velocity,considerable amount of wind energy can be harvested.By application of wind energy,considerable amount of fuel can be saved and /or tha ship's speed can be increased . In recent years , the application of aerodynamics has vastly improved the efficiency of sail-rigs and the prospect of application of wind energy for ship propulsion is growing.Developing countries such as Indonesia (Schenzle 1983) and Fiji (Macalister 1985) already have a wind-assisted ship propulsion program.

Recent research efforts have greatly improved efficiency of conventional sail airfoils.New types of sail airfoils with better lift-to-drag ratio than conventional sail airfoils are possible.This has introduced sail airfoil with streamlined leading edge mast instead of ordinary circular mast(Chapleo 1968).In order to improve efficiency of airfoil,double sided membranes wrapped over a rigid cylindrical leading edge have been used(Sweeney 1961,Fink 1967,Robert et al. 1979).Ormiston

Sailwing,a double

membrane airfoil with a circular leading edge and a taut wire as trailing edge.

Hence this thesis is divided mainly in two parts- the first part(Chapter 2) deals with wind energy application in ship propulsion as an auxiliary power source so that fuel consumption due to the main power source,a diesel engine,can be reduced.The second part(Chapter 3) deals with experiments,which are carried out on double membrane sail airfoil with cusped trailing edge. Chapter 4 deals with the need for future R&D and points out the scope for future work.

CHAPTER 2

WIND ENERGY APPLICATION TO SHIP PROPULSION : REVIEW & RECOMMENDATIONS

ABSTRACT

Wind assisted sail power can be used in ship propulsion as an auxiliary energy source in order to reduce fuel consumption . A review of research in this area is presented by bringing togehter diverse informations from aerodynamics,ship science and meteorology .Various sail types have been assesed and the manually controlled cat rig is recommended for a developing country like India. Estimated fuel saving due to sail assist in Indian coastal shipping is 20 % of the present consumption, on the basis of available maritime statistics.The possibility of considerable saving saving in fuel and foreign exchange against a small capital investment is pointed out .

(2.1) INTRODUCTION :

Wind energy has long been thought of as a renewable source of energy , whereas many other sources -oil,coal etc. are exhaustible.Due to the current energy crisis interest in wind energy has increased as fossil fuel costs and demand for power increase continually.Wind power available at a location is proportional to the cube of wind velocity.So it is evident that in regions of high wind velocity, considerable amount of energy can be extracted from the wind.Above all,wind energy is clean and pollution free.Wind energy can be used as an auxilliary means of propulsion in ships by installing sail-rig. The technology of sail has been vastly improved by application of application of modern aerodynamics,in recent years.This chapter attempts to bring under one head important informations and concepts from aerodynamics,ship science,maritime transport statistics,wind meteorology and fuel economy.It is hoped that this approach will facilitate the technical planning process and R & D activities.

The term sail-assist is applicable to the ships in which most of the propulsive power is developed by a fossil fuel engine and sail-power is used to save a part of the fuel and/ or to increase speed.In fact,the prospect for application of wind energy is very good over water areas,such as sea,large lake etc.,because wind tends to be stronger than on land.That wind speed and relative energy increase rapidly from rough terrain to smooth terrain,the sea being the smoothest,can be observed from Table 1 and Fig. 1(Selzer 1986).(Fig.1 gives distribution at a particular location where wind speed at 1000m height is 10 m/s.) Fig. 2a & 2b show how wind speed increases from land to sea and also how closely the isovents follow the coast line(Selzer 1986).Fig.2a illustrates the point for an island and Fig.2b for a coastline which is part

of a continent.Various types of sail-rigs have been developed over the years.Wind Ship,an American Company,tested several rigs in the sail-assist mode on ships,out of which a 3000sq.ft (= 278.70 m^2) soft sail cat rig and a 90 sq.ft(= 8.36 m^2) Magnus rotor(rotating cylinder) are promising.They have also tested a 300 sq.ft(= 27.87 m^2) model of wing sail(Bergeson et al.1981).A cat rig has a soft canvas sail whereas a wing sail has an aircraft wing like structure and appearance.This chapter discusses the characteristics of the three types of sail-rigs,their economic and technical merits and finally how much fuel saving Indian shipping industry may realize if sail-rigs are installed on ships as auxiliary means of propulsion.Even on the existing fleet of ships, such sail rigs can be retro-fitted(i.e.,can be fitted later although not provided for originally) with minor modifications.Such a venture named INDOSAIL Project was undertaken by the Indonesian Ministry for Research and Technology.In fact the INDOSAIL vessel is expected in the long run to rely more on wind and use the engine only in auxiliary mode(Schenzle 1983).This vessel can vie with motor ships in all respects except speed by efficient utilisation of monsoon or trade winds over the Indonesian archipelago.INDOSAIL project is a first step towards the Wind-Solar Ship "KAPAL SURYA",which would be totally independent of fossil fuels(Schenzle 1983).In 1984 and 1985,Macalister Elliott and Partners Ltd.,with the assistance of the Government of Fiji and the Asian Development Bank carried out a project to retrofit(Fig.3b) the 300 tonne ship 'Na Mataisau'(Macalister 1985). Details of data recorded can be found in Asian Development Bank Report,TA No.508-FIJ,1985.Due to limited budget(US Dollars 40,000), they could not test mechanically controlled wing sail or Magnus rotor.The rig was manually controlled requiring minimum handling.The Fiji experiment was so promising that the investigators recommended that " no commercial ship should be designed

or built without considering auxiliary sail..." in the context of intraarchipelago shipping (Macalister and Akester 1985). The fuel price is likely to increase in the next decade for the oil importing developing countries which should stimulate further research in this field(Macalister 1985).

(2.2) TYPES OF SAIL-RIGS AND THEIR SELECTION :

Various types of sail rigs are shown in Fig.3a,including two different types of wind turbines.It can be shown that wind turbines in most cases can positively contribute to propulsive power(Bergeson et al. 1985, Blackford 1985).Square rigs operate by drag forces and hence they are very inefficient.The remaining rigs operate on the basis of lift forces and are quite efficient (Newman 1987).Princeton Sailwing is a sail aerofoil which is formed by wrapping a fabric over a rod, the ends of the fabric meeting at a sharp trailing edge.It has been named Princeton Sailwing because it was first tested at Princeton University (Sweeny 1961).Similar aerofoils were used on sailboats(Marchaj 1964). Performance of Princeton Sailwing depends on pressure within the aerofoil, stiffness , porosity, extensibility (Robert et al. 1979). So its good performance depends much on the maintenance . Thus its maintenance cost is high.It is heavy and difficult to make. Since maximum thickness is much forward than conventional aerofoil,such as the wing sail,it usually has higher drag . A sail rig is selected for a ship on the basis of the following considerations :

- propulsive performance of the sail rig
- initial cost of installation of the rig
- operating cost
- weight
- size(volume or area occupied by the system)
- safety while operating the rig

-cargo handling interference

-visibility

It has been observed that the stayed mast(of a fore and aft rig) which is supported by guy wires weighs almost as much as an unstayed mast.It also has poor aerodynamic performance and interferes with cargo handling.Hence unstayed rig is preferable.Bergeson et al (1985) conclude on the basis of the above factors that unstayed cat rig and wing sail have the good prospects for application in marine auxiliary propulsion.

(2.3) SAILING MECHANISM AND DIFFERENT MODES OF SAILING :

The forward component of the total aerodynamic force acting on the sail-rig helps in propelling the ship.This is illustrated in Fig.4(a).Fig.4(b) shows the aerodynamic forces acting on an aircraft,for the sake of comparision.The following are the different modes of sailing which are illustrated in Fig.5 wherein the velocity triangle defines true and apparent wind :

a) Running : When apparent wind is astern(the aft or rear portion of a ship is known as stern),the aerodynamic drag D provides forward thrust.The drag and lift coefficients C_D and C_L are obtained by dividing D and L by $\frac{1}{2}\rho V^2 S$, where ρ is the density of air,V is the velocity of apparent wind and S is the projected area. Since drag coefficient of any surface kept perpendicular to the wind is almost the same,there is not much scope for improving the propulsive power in this mode.

b)Reaching : When apparent wind is directly abeam(breadth of a ship is known as beam), the lift force L provides the thrust.Hence the maximum lift coefficient is the measure for comparing different rigs.

c)Close reaching: When the apparent wind is forward of abeam, drag reduces the propelling thrust.Though drag coefficient

at maximum lift coefficient is an important factor to consider, it is desirable to attain maximum lift coefficient and accept the corresponding drag coefficient (Bergeson et al 1985).

d) Head winds: When ship is proceeding windward, the rig is rendered inoperative and set at zero angle of attack to minimise drag which cannot be completely eliminated. The maximum lift coefficient $(C_L)_{max.}$ is the most important factor indicating performance of a rig for most of the operating modes. Note both C_D and C_L are functions of the angle of attack.

$$\frac{C_D \text{ at } (C_L)_{max}}{(C_L)_{max.}}$$

is the fraction of forward thrust lost due to drag in close reaching. C_{D_o} represents the drag at zero angle of attack and this is the the drag when the rig is inoperative, the ship moving windward. The aerodynamic performance for the rigs is tabulated in Table 2 .

(2.4) CAT RIG :

In 1981, 3000sq.ft cat rig was installed and tested by the Wind Ship Company on the cargo ship named m/v MINILACE. The general arrangement of cat rig is shown in Fig 6. As shown in the figure, a triangular piece of fabric is stretched between a vertical unstayed mast and a horizontal boom. In a storm or extremely gusty wind the sail can be lowered manually. The performance of the cat rig is illustrated in Fig 7. An automatic control system, which operates under normal conditions, has been developed. It performs the task of trimming the cat rig to get maximum thrust.

(2.5) MAGNUS ROTOR TEST AND EVALUATION :

Anton Flettner first predicted in 1920's that the Magnus rotor could be used as a sail-assist device (Flettner 1926). In 1983 Wind Ship company along with T.HANSEN of Windfree, Inc. tested a Magnus Rotor aboard 18ton, 42ft motor vessel TRACKER (Hansen 1977). The general arrangement is shown in

Fig.8. A cylinder rotating in a cross-flow,gets air accelerated on one side and retarded on other side.According to Bernoulli's Theorem,this gives rise to pressure difference and that causes generation of lift.This is the basic mechanism of generation of lift in Magnus rotor(Swanson 1961,Streeter et al.1975). A value of ($C_{L_{max}}$) upto 13 has been measured for a Magnus rotor (Bergeson et al. 1985).The Magnus rotor is structurally strong because of its shape.The lift force remains constant above a certain wind speed.This was demonstrated experimentally(Fig.9) by Flettner (1926).This is an insurance against a sudden strong gust of wind or a storm.Thus the Magnus rotor is inherently safe.Fig.10 shows the performance curves of a 90 sq.ft Magnus rotor.The Magnus rotor has the following advantages :

(i)Size : Compared to a cat rig of eqivalent area(projected area times maximum lift coefficient), the Magnus rotor will be less than 1/2 as tall and sail area centroid only about 2/3 as high above the deck . This is desirable for overall stability of the ship.

(ii)Structure:In case of soft sails and wing sails, the structure is heavy because it is required to carry the pressure force distributed over flat area down to the hull through masts and rigging of high aspect ratio.(High aspect ratio implies that the rig has a height much larger than its its average width).A cylinder because of its curvature can withstand better both the distributed pressure load and beam bending stress.An aspect ratio of 5 or 6 is sufficient for a rotor cylinder.

(iii)Deck Space requirement :Wing sail chord will be about six times the barrel (cylinder)diameter.A soft sail cat rig of the same effective or eqivalent area will have a boom length about 5 times the endplate diameter.Thus Magnus rotor requires far less deck space compared to other sail rigs.

(iv)Control:Since lift is always perpendicular to apparent

wind direction,it has no angle of attack or stall angle. Hence the problem of adjusting angle of attack is not present as compared to cat rig and wing sail.

(v)Safety:The danger of a swinging boom injuring personnel or damaging cargo is not present.Lower endplate has a guard rail preventing accidental contact with crew. Barrel and endplates have smooth surfaces and do not cause injury even while rotating.

(vi)Weight:A sail-assist device should be as light as possible,because it decreases the stability of the ship. (This has been further discussed in section 8). Magnus rotor system is the lightest sail assist device ever designed.

(vii)System Costs:Magnus rotor is very light and its components - masts , endplates , barrel are very simple to manufacture.The cost of installing Magnus rotor is the lowest if automatic control is envisaged for all three types of sail system.

(viii)Durability:Because of inherent load limiting capacity, it is safe in storms compared to other sail devices.Because of its toughness,high fatigue strength, corrosion resistance,fibreglass is a very suitable building material.However aluminium is also a good choice because of low cost .

(2.6) WING SAIL :

The idea of using a rigid aircraft-wing like structure for sail-assist of ship propulsion is due to Flettner (1926).In 1982 Wind Ship and Ceres Hellenic Shipping Enterprises Ltd. of Pireaus,Greece tested a 300 sq.ft Wing sail model. The general arrangement of the test rig is given in Fig. 11. This shows that the wing sail model has a flap.A flap is a section at the rear end of wing which can be rotated to get higher maximum lift coefficient at low velocity of wind(Houghton et al. 1988).

Aerodynamic Characteristics of Wing Sail Model

In the tests conducted by Bergeson et al(1985),the Reynolds number for model wing sail is 2.2 million and that of full scale model is 6.0 million .NACA 4 digit symmetrical sections were used since they show very small scale effect on lift curve slope for thickness ratios less than 12%(Renolds number between 3 and 9 million).For thickness ratio of 18% of the model,there will be some scale effect . For higher thickness ratios,model may have slightly lower value of lift than full scale sail (Abbot,et al. 1959, Bradbury,1980). Minimum drag coefficient C_{D_o} is an important factor to account for the power loss in the head wind when the wing sail is feathered i.e.aligned with the direction of wind (York 1981). C_{D_o} for NACA 4 digit symmetrcal airfoil is quite low, approximately 0.006 (Abbot et al 1959).The predicted drag polar for wing sail model is given in Fig 12.Maximum drag coefficient obtained was 1.2,a conservative estimate based on flat plate data(Hoerner 1965). Maximum lift coefficient was obtained from data given by Abbot et al(1938). Flap gap decreased maxmimum lift by 20%. To prevent this a foam seal was put(Abbott,et al. 1938).The lift vs angle of attack curve based on the test results of the model with 45 degree flap deflection is shown in Fig 13.Stall angle noted was 25 degree and $(C_L)_{max}$ = 2.0.Higher lift coefficients are possible with a more efficient aerofoil(say,NACA 5 digit with 12% thickness) with flap deflection (Scherer 1974).

The Wind Ship Company has developed an automatic control system for the wing sail. The control system will perform the following functions :

-Trim the wing sail to get maxmimum thrust

-Feather the wing sail automatically in storms

- Align the flap to reduce aerodynamic drag

(2.7) POTENTIAL FOR VARIOUS RIGS :

Fig.14 illustrates the fuel saving for various rigs on Mini-Lace.Table 3 compares predicted fuel saving for various rigs at average ship speed of 5.7 knot.The cat rig has the following advantages :

It has a low construction and material cost.Its design is simple and inexpesive because aeroelastic instability or flutter does not arise in fabric.As a result initial capital requirement is low unless it is automatically controlled.(In the Indian context,where labour is cheap the possibility of manual control makes the cat rig particularly attractive.) Costs for cat rig and wing sail,if automatic control is envisaged,are almost equal.So aerodynamic performance is important and wing sail has certain advantages over cat rig :

- high $(C_L)_{max}$, high L/D ratio
- low $\frac{C_D \text{ at } (C_L)_{max}}{(C_L)_{max}}$
- easier automatic control
- easier cargo handling since less deck space is required.

The main disadvantage of wing sail is that its design is complicated since it has to be designed against aeroelastic instability or flutter.

Present Value Model : The most common method of assessing the cost effectiveness of an installtion or device is by means of the present value model.It relies on the three following costs for making an assessment :

1)Initial investment (Io) , for retrofitting the sail-rig on a ship

2)Annual fuel cost (Fc), for the sail-assisted ship

3)Annual operational maintenance cost(Mc), of the rig Money allocated to be spent for maintenance of rig and for meeting fuel cost is allowed to get interest in bank.This model has the importance in that it can be used for comparing economic

viability of various rigs and arriving at a decision on what type of rig will be suitable for a particular ship. The model has been discussed by Tewari (1978) and leads to the following expression

$$PV = Io + \sum_{j=1}^{N} Fc/(1+Y)^{j} + \sum_{j=1}^{N} Mc/(1+Y)^{j} \qquad \text{------(1)}$$

where PV = present value

Fc = annual fuel cost at present

Mc = annual maintenance cost present

Y = rate of interest

N = life span of the ship in years. Assuming annual fuel price hike at the rate of r1 and annual inflation rate to be r2, equation (1) becomes :

$$PV = Io + \sum_{j=1}^{N} \frac{Fc\ (1+r1)^{j}}{(1+Y)^{j}} + \sum_{j=1}^{N} \frac{Mc\ (1+r2)^{j}}{(1+Y)^{j}}$$

Let $(1+r1)/(1+Y)=x1$, $(1+r2)/(1+Y)=x2$

$$\text{Then } PV = Io + Fc\sum_{j=1}^{N}(x1)^{j} + Mc\sum_{j=1}^{N}(x2)^{j} \qquad \text{-----(2)}$$

Applying the formula for the sum of a geometric progression, we get from equation (2) :

$$PV = Io + Fc\left[\frac{x1^{j} - 1}{x1 - 1}\right] + Mc\left[\frac{x2^{j} - 1}{x2 - 1}\right].$$

For a ship without sail, Io =0, Mc = 0. For a ship with sail-assist, rig cost Io and rig maintenance cost Mc have definite values. If the present value in the latter case (with sailassist) is less than the former, then it is evident that sail-assist will be economical. Different rigs will have different values for Io, Fc, Mc. To assess what type of rig will be attractive over the ship's life, say, for 15-20 years, calculation based on the present value model is to be carried out. Bergeson et al. (1985) mention that initial investment required for cat rig and wing sail (both with automatic controls) is more or less the same. Comparing average performance at ship speed of 6 knots and wind speed of 13.7 knots when the distribution is as shown in

Fig.15a, wing sail saves 32%, cat rig 26% and Magnus rotor 20% of fuel, after deducting the power required for spinning the rotor, (Fig 15b). Assuming maintenance cost to be the same for all rigs, the rotor cost must be less than 83% of the cost of the cat rig and less than 63% of the cost of wing sail to be economically competitive, according to Bergeson et al. (1985). Rotor more than meets the above conditions (Bergeson et al. 1985). Taking into account the advantages of Magnus rotor over other sail-assist devices, it may be commonly used as a sail-assist device in a futuristic scenario where automatic control is a must. It has already been mentioned that in the Indian context manual control may be attractive and the Magnus rotor may not be the best option. Io for the cat rig will be very low without automatic controls . The cat rig will be low on maintenance but somewhat higher on operational cost due to manual control inspite of low labour wages. In the absence of any experimental trial , it is a matter of conjecture if a manually controlled cat rig will score over the rotor. The experience of the Fiji Islands (Macalister 1985) also draws attention to soft sail rigs with manual control.

(2.8) EFFECT OF SAIL-RIG ON STABILITY OF SHIPS:

Installation of sail rig may cause, if proper care is not taken, a reduction in stability of the ship. Before going into how installation of sail-rig affects ship stability, it will be appropriate to discuss briefly the stability of a ship in general (Rawson et al. 1968). Fig.16(a) shows a ship in upright condition when the weight W of the ship and buoyancy W act along the same vertical line XX which is the axis of symmetry. WL is the waterline, G is center of gravity, Bo the initial center of buoyancy. When an external heeling moment (due to say, gust, waves etc.) acts on the ship, the ship heels through an angle ϕ (Fig.16b). The new center of buoyancy is B .

Since weight and buoyancy does not act along the same vertical line, they create a moment which is designated as Righting Moment.The point of intersection (M) of the line XX and the line of action of buoyancy is known as metacenter.It is evident from the figure that if M is above G,then righting moment opposes the heeling moment.Hence for stability of the ship,it is essential that M is above G. From Fig.16(b), Righting Moment = $W \times GZ = W \times GM \times SIN\phi$ where GM and GZ are known as metacentric height and righting lever respectively. For small angles,M doesnot shift appreciablly with varying ϕ and hence GM remains constant.It is obvious that the more is the righting moment,the more is the stability of the ship i.e. the ship can resist the heeling moment more effective ly.For a constant weight of W,righting moment will be more if GZ is more.Hence stability of a ship is presented in terms of GZ . Since $GZ=GM(SIN\phi)$,we need the c.g. of ship to be as low as possible for increased GM.A typical Static Stability curve (GZ vs ϕ curve) is shown in Fig.(17). In the limiting case , $SIN\phi \rightarrow \phi$ which implies $GZ = GM \times \phi$ For fixed G and M, $\frac{dGZ}{d\phi}$ = GM i.e. slope of the GZ vs ϕ curve at origin is GM.Thus GM can be easily measured as shown in Fig. 17, by drawing a line parallel to GZ axis at ϕ = 1 radian so as to cut the tangent line drawn at origin.

A sail rig can affect the stability in two ways :

(i)Due to weight of sail-rig,the c.g. of the system will go up,thereby reducing GM and hence static stability.

(ii)Due to wind pressure on exposed area,the sail will cause additional heeling moment . In the Fiji trial,the heelangle chosen was 10 degree,at 16 knots apparent wind.Reefing of sail started at about 12 degree to avoid any danger (with tanks ballasted or with equivalent cargo) according to Macali-ster (1985). For a retrofit sail-rig,the above problems can be counteracted by bringing the c.g. of the ship down,by increa-

sing water in ballast tanks.For a ship which is to be designed to carry a sail-rig from the very beginning , stability requirements demand that it should have adequate breadth. However it is seen that sail-rig installation does not significantly affect stability of large ships.Butit is desirable that the sail-rig should be as light as possible.Therfore soft sail cat rig has an advantage over metallic wing sail and Magnus rotor.The sail rig slows down any heeling motion due to air resistance or damping acting on the sail area,and thus improves passenger comfort(Macalister 1985).Here again the cat rig has an advantage over others because of larger area.

(2.9) INDIAN COASTAL SHIPPING :

Consider a vessel sailing from Calcutta to Vishakhapatnam.To estimate the fuel saving that can be achieved by wind assistance,we utilize the wind data given by Mani et al.(1983. For calculation of fuel saving due to wind assistance,we use wind velocity at Puri,which is midway between Calcutta and Vishakhapatnam,and wind rose of Bhubaneshwar since that of Puri is not available.We assume that the meteorological sites are well away from the towns and cities and in the case of the two stations mentioned above they are close to the coast line.Therefore they belong to the roughness class 1 of Selzer (1986).Since wind speed increases rapidly as one moves away from the coast into the sea,an energy increase of 40% is assumed(Selzer 1986). The vessel chosen by Bergeson et al(1985) is the 3000 tonnes deadweight general purpose cargo ship m/v MINI LACE which has the following characteristics (Naval termininology used here are defined in Rawson et al (1968)) :

Displacemennt(average)	2951.625 metric ton(2905 long tons)
Service speed	8 knots(4.115 m/sec)
Installed Power	1000 h.p.
Specific Fuel Consumption	2.232×10^{-4} ton/hp-hr
Sail size(cat rig)	3000sq.ft(278.709 sq.metre)

Operating speed 7 knots(3.6 m/sec)

In order to estimate fuel saving,we observe that the Mini Lace is much like a typical general purpose cargo vessel used along the eastern coast in India.The ship's resistance characteristics are given in Fig.(18) (Guldhammer, et al.1974).From this curve, for an average displacement given above ,the ship has a resistance of 26334.49 N when its speed is 7 knots(1 knot = 0.5144 m/s). This is the operating speed of MINILACE and power curves for this ship speed are given in Fig. 7.

Effective Power = (Resistance)X(velocity of the ship)

Power required to run the ship at constant speed of 7 knot = 26334.49X(7)X(0.5144) watt =127.16 HP.The ship has a propulsive efficiency = 0.35 (Bergeson et al 1985). Therefore, the power that should be generated by the engine to run the ship at speed of 7 knots = 127.16/0.35 HP =363.31 HP.The procedure of calculation of fuel saving is given below.

The number of sailing hours per annum of a ship has to be determined from primary data given in " Basic Port Statistics of India 1987 - 88 " (Ref. 5).This involves several steps.Total cargo handled in coastal shipping in 1987-88 (including all major and minor ports) = 46.5 million tonnes.Total cargo handled by primitive and manpowered sailing vessels at minor / intermediate ports =0.488212 million tonnes.Total cargo handled by motor-propelled ships=46500000-488212=46011788 tonnes . Total number of ships involved in coastal shipping = 146 (India's Overseas Shipping Statistics 1988-89).Cargo handled per ship in coastal shipping =46011788/146=315149.23 tonnes.Output per ship berthday in 1988 is 3508 tonnes(Ref.5,pp.(ii)).Number of berthdays required/ship to handle cargo(in a year) =315149.23/3508 =89.83= 90 days. Average port turn-around time is 8.1 days(Ref.5, pp.(ii)).Number of times a ship takes berth in a year = 89.83/8.1 = 11.09 = 11 times approximately.Average pre-berth detention is 2.2 days(Ref.5,pp.(ii)).Total preberth detention/ship in a year = 11X2.2 =24.4 days.Total number

of days a ship is involved in cargo handling = 90+24 = 114 days. Therefore number of days a ship is at sea = 365-114 = 251. Therefore total HP-hrs required per annum without sail assist = 251X24X363.31 = 2.188×10^6.

Wind rose and velocity for the months of March, April and May are approximately the same. So for calculation of fuel saving for these months, the wind rose and velocity of May are used. From the wind rose we can obtain the wind angle, where wind angle is defined as the angle between the direction of ship motion and the wind. The sailing hours for a month is 24X31X(251/365)= 511.62 hrs, where a ship remains on voyage for 251 days out of 365 in a year, as shown before. For the months of June and July when a ship is going from Calcutta to Vishakhapatnam, the wind angle is 47 degree for 24 % and 25 degrees for 14% of the sailing hours. For the remaining hours, the wind flows from different directions. Much of this wind can be easily utilized. However, for the sake of simplifying calculations we shall consider only the predominant winds for the time being. Similar procedure is followed for the other months. Table 4 and show the calculations for outward and return journeis. From the above tables we get the total energy saved to be 1.542×10^5 HP-hrs. Hence the net fuel saving is 7 % per annum due to wind assistance in Indian Coastal Shipping. Since we have considered only the predominant wind directions, ignoring contribution from the rest, 7 % saving is very much an underestimation. It can safely be said that saving will be approximately 10%. The breakup of different types of ships involved in Indian Coastal Shipping for the year 1988 is not available although the total number of vessels is known to be 146. This breakup however is available for the year 1981 (Workshop on Future of Indian Shipping 1981, pp. I-2) and we assume that the same proportion remains valid for 1988. The number of dry cargo liners, tankers and passenger-cum- cargo vessels deployed in coastal shipping in 1988 turn out to be 91, 29 and 26 respectively. We recall that average number of days a ship remains at sea per annum is 251.

The average daily fuel consumption of these three categories are given in column D of Table 6 .Total annual fuel consumption calculated in the same manner as in Table 6 turns out to be 1161880 tonnes.Hence 10% fuel saving per annum will lead to a saving of 116188 tonnes.

(2.10) INDIAN OVERSEAS SHIPPING :

Calculation of fuel consumption for overseas shipping by Indian vessels is shown in Table 6,the total being 1260660 tonnes per annum.The experiment with the ship Mini-Lace(Ref.7) was conducted between Houston,USA and Panama.This route is on the high sea as distinct from a coastal route.The prevalent wind in this zone is the North East Trade wind.The average fuel saving achieved by Mini Lace was 20 %.Indian overseas shipping like many other shipping in the world occurs mostly in the trade wind zone.Therefore 20 % fuel saving is assumed also for Indian overseas shipping which gives a total annual saving of 252132 tonnes approximately.

(2.11) CONCLUSION :

The cat rig appears to be the most promising for retrofitting on Indian ships because of its low design and installation cost and easy handling.The annual fuel saving expected due to a sail-assist device is 116188 tonnes for Coastal Shipping and 252132 tonnes for Overseas Shipping.Total annual fuel saving that can be achieved by Indian shipping will be 368320 tonnes which is of worth Rs.569 million(31.63 million dollars) approximately,taking average fuel oil price to be $85.9 per ton,price prevalent in Bombay harbour (Ref. 16,Table 5.1).This entire amount will be in foreign currency since India is an oil importing country.India,like most developing countries,has a balance of payment problem and therefore the importance of reduction in fuel oil consumption is immense.The wind assist device (the cat rig) which is recommended here has a low capital requirement and a short gestation period .Hence it is particularly suitable for India(and any developing country) which has its own

shipping industry.Hence it is recommended that India should invest in R & D in this area,where the benefits are likely to be considerable for a small capital outlay .

EXPERIMENTAL SET-UP AND EXPERIMENT

(3.1) INTRODUCTION :

One simple way of making a low speed aerofoil is to wrap a fabric around a circular rod,bringing the two ends of the fabric to meet at a rigid trailing edge.In this case,the circular rod forms the leading edge.Under wind load,the aerofoil becomes cambered. Since camber increases with angle of attack,the aerofoil generally has high lift curve slope and high maximum lift coefficient.But since maximum thickness is much forward,it usuallly has higher drag than conventional rigid aerofoil.Drag decreases when faabric of very low porosity is used.The performance of this type of aerofoil depends on the Renolds number,pressure within aerofoil and the stiffness,extensibilty and porosity of the fabric , all expressed non-dimensionally(Newman and Ngabo 1978).

The advantages of such an aerofoil is that it is light, cheap and easily foldable(Stong 1974).The aerofoil is found to be stable under wind load without any tendency to flap. This can be used on sail-boats,hang gliders and also wind turbines.

Tests on such an aerofoil was carried out by Newman et al (1979) with a sharp trailing edge.It was decided to carry out the present experiment with a cusped trailing-edge,keeping all other parameters as close to Newman et al(1979) as possible . The aerofoil was tested for three different tunnel speeds of 12, 15 and 17 m/sec.It was decided to carry out the test for two leading edge radii with taut thickness-to-chord ratio of 9.7 % and 13%.The distance between the leading edge rod and trailing edge was varied to give different camber and tension to the fabric.Test was carried out with fabric of weight 40 g/m^2.The lift and drag of the aerofoil was measured for different chord

lenghs and Reynolds numbers.

(3.2) APPARATUS :

Test was carried out in the three dimensional arm of closed circuit low speed two arms wind tunnel, IIT Kanpur. The test section size is 167 cm X 91 cm X 61 cm (Fig. 19). The model was mounted horizontally between two aluminium circular discs. The aerofoil was formed using aluminium pipe as leading edge and a cusped rigid trailing edge . It was decided to go for a trailing edge with cusp for achieving better performance . The latter was freely pivoted at the two extreme ends on the discs. This allowed the fabric to take its natural shape(Fig.20).

(3.3) DETAILS OF VARIOUS COMPONENTS OF EXPERIMENTAL SET-UP :

(3.3.1) CIRCULAR DISCS :

Two aluminium circular discs each of diameter of 472 mm and thickness 3 mm were used as sidewalls and the 2D model was mounted spanning the walls. Circular disc was chosen in order to avoid the inconvenience of measuring tare drag for each angle of attack of aerofoil. The edges of the discs were chamfered to ensure the flow within the discs to be two dimensional and also to reduce tare drag .

Two rectangular slots each of size 18 mm X 12 mm were made to insert the leading edge rod through the disc. This provided for changing the chord length of the model by shifting the leading edge pipe back and forth, maintaining the trailing edge in position. In order to support the trailing edge piece, threaded hole was made on the discs to hold the pin. Four holes were drilled on each discs to insert circular rods(Fig.21).

(3.3.2) CIRCULAR RODS :

Four circular rods of mild steel were used to hold the the two discs in position . After properly tightening with nut, the two discs alongwith four rods act as a single rigid body. Initially the rod diameter chosen was 5 mm. Later while mounting on three struts of three component balance, it was found to be

too weak to bear the total weight of the whole set-up . So the experiment was repeated with four rods of 9 mm diameter(Fig.21).

(3.3.3) LEADING EDGE PIPES :

Two aluminium pipes of 25 mm and 33 mm outer diameters were chosen to serve as leading edge of model.Aluminium pipe instead of rod was chosen to make the model light,thus keeping the weight of the set-up within limits allowed by three component balance.Each of the pipes had threaded bolts at both ends in order to tighten it against the discs with nuts(Fig.22).

(3.3.4) TRAILING EDGE PIECES :

Two pieces of trailing edge with cusp were prepared. A mathematical cusp is defined as a point where two surfaces meet at a sharp edge but have the same tangent.This would result in a zero thickness sharp trailing edge and is not a practical shape.In the present case some thickness,very small compared to chord length,is introduced.The trailing edge piece was needed to be as light as possible.Also it should have enough thickness to make a hole of 1.6 mm diameter in order to insert the pin through it.Thus it had two parts ,one made of teak wood and other part was a rectangular plate of mild steel with 3 mm thickness.The wooden part had a groove throughout its length and the M.S. plate was inserted into it (Fig.23).This as a whole now make the trailing edge piece.The hole for inserting pin was made on the plate at the position of centre of gravity of the trailing edge piece.

(3.4) EXPERIMENTAL PROCEDURE :

The rear strut of the balance can be moved up and down. This allows to change the angle of attack of the model.The balance has a provision of moving the rear strut up resulting in 40 degrees angle of attack for the model and down resulting in 20 angle of attack from zero degree i.e. balance level condition. Initially it was decided to carry out the experiment for angle of attack from 0°-40° , 45°-85° , 180°-140° , 135°-95°.However due to limit-

ations on allowable pitching moment acting on the balance , test was carried out upto angle of attack of 20^{o}.The model was so arranged as to have an initial angle of attack of zero degree at the uppermost position of the rear strut.The rear strut was then lowered to balance level condition by successive 5 degrees,thus increasing angle of attack from 0^{o} to 20^{o} .In this set-up,lift acted upward, thus counteracting the weight of the system.

The nylon fabric was wrapped over the leading edge and trailing edge piece.The ends of the trailing edge piece were stitched.The fabric was glued to the trailing edge piece over a small distance of 5 mm to ensure that under wind load the fabric keeps in flush with the trailing edge.Equal weights of amount two kgs were hung from both the ends of the leading edge pipe to ensure equal extension of both the ends and to keep the fabric in sufficient tension.The leading edge pipe was then properly tightened with nuts.It was ensured that trailing edge piece was freely moving up and down,without any additional friction.Lift and drag were measured for angle of attack of 0^{o} to 20^{o} for three different chord lengths each with three different tunnel speeds of 12,15 and 17 m/sec.The experiments were carried out for chord lenghts of 261.0 ,259.5 ,258.0 mm which represent taut,slightly loose and loose cases respectively.
The experiment was repeated with the same set for which lift acted down.Lift and drag values were measured for the set up without model.This gave tare drag.This was substracted from the readings for the model to obtain correct lift and drag.

(3.5) EXPERIMENTAL RESULTS :

In order to obtain correct values of lift and drag,calibration of the three component balance was done.Calibration results for lift and drag are plotted in Figs.24 and 25 .Lift and drag values obtained by the balance were multiplied by factors of 0.9983 and 1.1236 to obtain correct values of lift and drag .

Lift and drag coefficients for the aerofoil are shown respectively in Figs.26-31 and Figs.32-37.The lift and drag coefficients for angle of attack between 0° to 20° for three different cases(different chord lenghts) are tabulated in Tables 7 and 8 .

Lift coefficient is non-zero and positive(very small) at zero angle of attack.This is due to initial camber due to flexiblity of fabric of the aerofoil.The shape of the aerofoil could be observed through the transparent perspex sheet at the side of the test section.The aerofoil was found to be increasingly cambered with increasing angle of attack.The aerofoil did not show any tendency to flap even in loose condition. Increase of camber ratio for a uniformly loaded membrane of small camber can be obtained on the basis of an approximate analysis(Robert et al. 1979).The following expression shows that increase of camber ratio

$$\Delta\epsilon = \frac{C_N \frac{1}{2}\rho U^2 c}{k\ 64\epsilon^2} \qquad \text{----- (3)}$$

where C_N is the normal force coefficient

k is the elasticity constant of the membrane(tension/unit width/unit strain)

ϵ is the initial,unloaded,camber ratio

Thus the increase of camber is proportional to the square of wind speed and is much greater when the initial camber is small as in taut cases. Moreover it is proportional to the normal force coefficient which generally increases from 0° to 90° and decreases from 90° to 180°.

(3.6) ANALYSIS OF RESULTS :

For the second set of experiments lift coefficient was found to decrease for increasing Reynolds number.Drag coefficient was also found to decrease (Table 8).But in the first set of experiments ,lift and drag coefficients were found to

to increase with Reynolds number.From (3) of section (3.5), it can be easily observed that camber increases with increase in dynamic pressure.Therefore lift coefficient should increase with increasing dynamic pressure due to associated increase of camber.Also lift at zero angle angle of attack and fixed tunnel speed increases with slackness of fabric due to associated increase of camber.

Sweeney(1961) made wind tunnel tests on a sailwing with leading edge diameter 12 % of the mean chord ,aspect ratio of 6 and a taper ratio of 1/3.Tests were carried out with cotton duck sails,first untreated and then treated with wax to reduce porosity . Data for the tests are available for two Reynolds numbers and angle of attack 0° to 15°.Though the amount of trailing edge tension is not mentioned,the fabric was very taut (Robert et al. 1979).So the lift and drag coefficients of Sweeney(1961) at Reynolds number of 15×10^{4} are compared with experimental results(with lift acting down) of taut nylon at Reynolds number of 20.67×10^{4}.Lift coefficients of Sweeney(1961) show stall at angle of attack of 14 whereas the present experimental results does not show stall even at 20° . The treated cotton duck shows comparable results with maximum lift coefficient of 0.82,the lift coefficient for taut nylon being 0.79 at 20°.The lift coefficient for untreated cotton duck was more than treated one.Drag coefficient for untreated cotton duck is more than treated one.This is accounted for by more porosity in the former case.Drag coefficient at 15° angle of attack for the present experiments is found to be higher than that of untreated cotton duck by 102.4 %.Drag coefficients for the present experiments at smaller angles of attack are higher by more than the above mentioned figure.

Lift and drag coefficients are compared with those of Robert et al.(1979).Lift coefficients for Robert et al.(1979) are found to be more than present experimental results.Also drag

coefficients for the former are less than the experimental results . However it is observed that the present experiment does not show stall even at 20 whereas results of Robert et al. (1979) show stall at 10 and 15 for taut and loose nylon respectively.

CHAPTER 4

CONCLUSION AND SCOPE FOR FURTHER RESEARCH

(4.1) CONCLUSION :

The first part(Chapter 2) of this thesis deals with wind energy application for ship propulsion with implications for Indian coastal and overseas shipping.The prospects of various types of sail rigs have been examined.Finally it is concluded that cat rig with manual control appears to be the most promising for retrofitting on Indian ships.An estimation done shows that India can achieve total annual fuel saving of Rs.569 million .The second part of the thesis deals with experiments conducted on a sail aerofoil with a circular pipe as leading edge and a cusped trailing edge piece.The leading edge could be moved back and forth relative to the trailing edge .This allowed for changing the chord length and thus giving the fabric different tension.Though the trailing edge was fixed in position,it could rotate without any additional friction.This allowed the fabric to take natural shape.Tests were carried for three different chord lenghts each with three different Reynolds numbers.Due to limitations of balance,tests were carried out up to an angle of attack of 20 degree . Present experimental results were compared with those of Sweeney(1961) and Robert et al(1979). Present experimental results show good agreement with Sweeney (196 for smaller angles of attack upto 3 degrees.Robert et al (1979) achieved much higher lift coefficients and lower drag coefficients than present experiments.

(4.2) SCOPE FOR FURTHER RESEARCH :

The main defect of present experiment is that at higher angles of attack ,the results are not valid.This is because at higher angles of attack,the aerofoil obstructs the flow between the two discs(side walls).The flow thus deviates from the aerofoil and passes through the gaps between the discs and the wind tunnel walls.Thus due to obstruction of flow between the discs,velocity over the aerofoil is smaller than indicated by the pitot-static tube kept far ahead of the model.Also due to deviation of flow from the aerofoil,the flow no longer remains two dimensional at higher angles of attack and there is spillage of flow through the gap between discs and the tunnel walls.These two factors - retardation of velocity and loss of flow over the model causes lower lift coefficient.Also the spillage of flow implies that the discs(side walls) are not at 0^{o} angle of attack and hence causes higher drag.This explains why the lift coefficient of present experiment is low and drag coefficient is high .

The present defect can be rectified if the aerofoil spans throughout the breadth of the tunnel.In order to check flow in the gap between the walls and the discs,vertical shrouds should be placed in front of the discs.To maintain two dimensional flow the front edges of the shrouds should be streamlined.

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Table 1 Types of Terrain and Roughness Classes(Ref. 25)

Roughness Class	Terrain	Relative Energy
0	water areas	10
1	open country ares with very few bushes,trees,and buildings	7
2	farmland with scattered buildings and hedges with separation in excess of 1000m	6
3	built-up ares,forests and farmland with many hedges	3

Table 2 Measures of Aerodynamic performance for rig alternatives (2D Section Data) : Ref. 7

Rig	$C_{L_{max}}$	$\frac{C_D \text{ at } (C_L)_{max}}{C_{L_{max}}}$	$\frac{C_{D_o}}{C_{L_{max}}}$
Stayed Fore and Aft	1.5	0.091	0.092
Unstayed Cat	1.5	0.084	0.063
Square	1.5	0.122	0.107
Princeton Sail Wing	1.6	0.035	0.075
Wing Sail(no flap)	1.0	0.037	0.022
(plain flap)	2.0	0.051	0.011
Flettner Rotor	10.0	---	0.113

Table 3 Comparison of predicted savings with various sail power units at average ship speed of 5.7 knots(Ref.7)

Sail Power Unit	Nominal Sail Area (sq.ft)	Design Wind Speed (knot)	% Daily Fuel Saving
Cat Rig	3000	35	31
Cat Rig	3000	25	28
Wing Sail	3000	40	43
Rotor	450	25	25

Table 4 : Energy(HP-hr) saved by Sail Assist in outward journey from Calcutta to Vishakhapatnam.

Ship speed = 7 knots = 3.6 m/s ; total sailing hour per month(TSH) for outward journey = 511.62/2hrs = 255.81 hrs

Months	Wind Velocity (kmph)	Wind Angle (Degree) A	Frequency B	Available Sailing hours C=TSH×B	Sail Power Available, obtained from Fig.7 D	Energy Saved in HP-hrs E = C×D
October, November, December, January	11.5	47	0.14	35.81	14.43	516.73
		95	0.10	25.58	29	741.82
		137	0.20	51.16	19.24	984.31
February	14.4	47	0.41	104.88	46.66	4893.79
March, April, May	23.6	47	0.41	104.88	134.39	14095.105
June	22.2	47	0.24	61.39	108.87	6684.00
July		25	0.14	35.81	31.1	1113.79
August	17.1	47	0.24	61.39	49.75	3054.15
		25	0.14	35.81	16.36	585.85
September	12.8	47	0.24	61.39	20.86	1280.59

Table 5 : Energy(HP-hr) saved by Sail Assist in return journey from Vishakhapatnam to Calcutta

Ship speed = 7 knots = 3.6 m/s ; total sailing hours per month(TSH) for return journey = 511.62/2 = 255.81 hrs.

Months	Wind Velocity (kmph)	Wind Angle (Degree) A	Frequency B	Available Sailing Hours C= TSH$\times$B	Sail Power Available, obtained from Fig.7 D	Energy Saved in HP-hrs E = C$\times$D
October, November, December, January	11.5	43	0.20	51.16	19.22	983.29
		85	0.10	25.58	30.0	767.74
		133	0.14	35.81	19.24	688.98
February	14.4	133	0.41	104.88	46.66	4893.70
March	23.6	180	0.10	25.58	15.55	397.76
April		158	0.17	43.48	31.10	1352.22
May		133	0.41	104.88	108.87	11418.28
June	22.2	178	0.20	51.16	15.55	795.53
July		155	0.14	35.81	46.66	1670.89
		133	0.24	61.39	108.87	6683.53
August	17.1	155	0.14	35.81	21.32	763.47
		133	0.24	61.39	49.75	3054.15
September	12.8	133	0.24	61.39	20.85	1279.98

Table 6 : Total annual fuel consumption due to Indian overseas shipping without wind assistance (Ref. 10 , Table 3.1 to 3.5)

Ship Types	Number	Average Number of days at sea per annum	Average daily fuel consumption(tonnes)	Fuel Consumption per annum(tonnes)
A	B	C	D	E = BXCXD
Dry Cargo Liner	86	121	22.1	229972.6
Dry Cargo Bulk Carrier	95	168	30.6	488376
Tanker	48	183	57.1	501566.4
Dry Cargo Smaller Tramp	1	145	22.7	3291.5
Passenger-cum-cargo	1	130	37	4810
Ore/Oil Bulk Carrier	9	62	58.5	32643
Total	240	---	----	1260659.5 tonr

Table 7 Lift and drag coefficients for the present experiments with lift acting up.

Taut nylon, chord length = 261 mm

Reynolds no. \ α°	C_L 0	5	10	15	20
20.67×10^4	0.1489	0.3755	0.4971	0.5268	0.7925
25.84×10^4	0.1440	0.3649	0.5083	0.6386	0.7988
29.28×10^4	0.1528	0.3684	0.5152	0.6540	0.8224

Reynolds no. \ α°	C_D 0	5	10	15	20
20.67×10^4	0.1006	0.1853	0.2753	0.3667	0.4786
25.84×10^4	0.1063	0.1858	0.2877	0.3814	0.4848
29.28×10^4	0.0998	0.1913	0.2969	0.3860	0.5074

Slightly loose nylon, chord length = 259.5 mm

Reynolds no. \ α°	C_L 0	5	10	15	20
20.51×10^4	0.2425	0.4313	0.6166	0.6864	0.8171
25.64×10^4	0.2343	0.4178	0.5564	0.6970	0.8408
29.06×10^4	0.2358	0.4243	0.5714	0.6979	0.8620

Reynolds no. \ α°	C_D 0	5	10	15	20
20.51×10^4	0.1173	0.2045	0.2767	0.3779	0.4827
25.64×10^4	0.1151	0.1968	0.2914	0.3923	0.5033
29.06×10^4	0.1201	0.1970	0.2966	0.4000	0.5234

Table 7 - continued

Loose nylon, chord length = 258.0

Reynolds no. \ α°	C_L 0	5	10	15	20
20.43×10^4	-0.1205	0.4758	0.6194	0.7609	0.9088
25.54×10^4	-0.1069	0.4657	0.6106	0.7680	0.9229
28.95×10^4	-0.0921	0.4665	0.6259	0.7751	0.9262

Reynolds no. \ α°	C_D 0	5	10	15	20
20.43×10^4	0.1128	0.2083	0.2955	0.4063	0.5263
25.54×10^4	0.1247	0.2105	0.3055	0.4240	0.5434
28.95×10^4	0.1223	0.2160	0.3143	0.4341	0.5529

Table 8 Lift and drag coefficients for the present experiments with lift acting down

Taut nylon, chord length= 261 mm

	C_L				
α°	0	5	10	15	20
Reynolds no.					
20.67×10^4	-0.0119	0.3701	0.4965	0.6594	0.7937
25.84×10	0.1875	0.3429	0.4845	0.6053	0.7577
29.28×10	0.1847	0.3287	0.4650	0.6045	0.7800

	C_D				
α°	0	5	10	15	20
Reynolds no.					
20.67×10^4	0.1207	0.2708	0.3604	0.4846	0.6036
25.84×10^4	0.1688	0.2421	0.3377	0.4176	0.5502
29.28×10^4	0.1619	0.2221	0.3159	0.4162	0.5729

Slightly loose nylon, chord length = 259.5

	C_L				
α°	0	5	10	15	20
Reynolds no.					
20.51×10^4	0.3126	0.4627	0.6110	0.7400	0.8864
25.64×10^4	0.2849	0.4401	0.5784	0.7244	0.8794
29.06×10^4	0.2687	0.4273	0.5676	0.7009	0.8546

	C_D				
α°	0	5	10	15	20
Reynolds no.					
20.51×10^4	0.2336	0.2986	0.4093	0.5124	0.6407
25.64×10^4	0.1704	0.2552	0.3459	0.4559	0.5932
29.06×10^4	0.1840	0.2633	0.3522	0.4371	0.5739

Table 8 - continued

Loose nylon, chord length = 258.0 mm

	C_L				
α^o	0	5	10	15	20
Reynolds no.					
20.43×10^4	0.3348	0.5378	0.6612	0.8082	0.9517
25.54×10^4	0.2922	0.4790	0.6186	0.7614	0.9037
28.95×10^4	0.2750	0.4703	0.6037	0.7441	0.8894

	C_D				
α^o	0	5	10	15	20
Reynolds no.					
20.43×10^4	0.2330	0.3222	0.4072	0.5157	0.6560
25.54×10^4	0.1816	0.2627	0.3582	0.4668	0.5942
28.95×10^4	0.1700	0.2542	0.3491	0.4505	0.5933

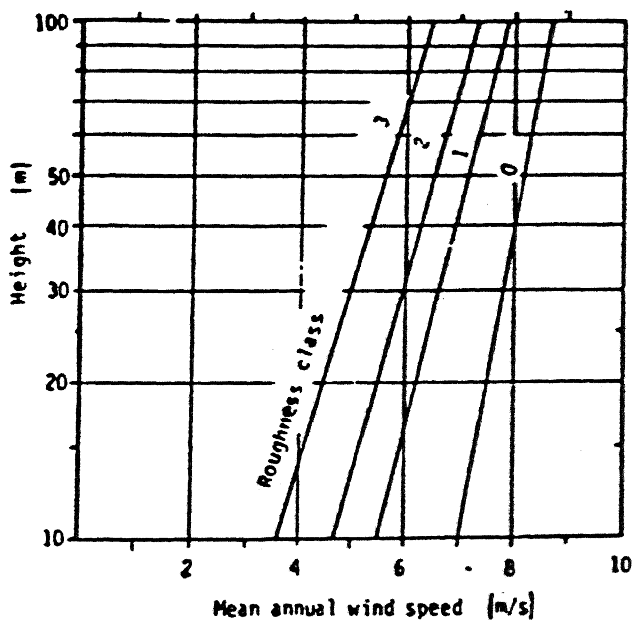


FIG. 1 WIND SPEED VARIATION WITH HEIGHT FOR DIFFERENT TERRAINS (REFER TO TABLE 1) (REF. 25)

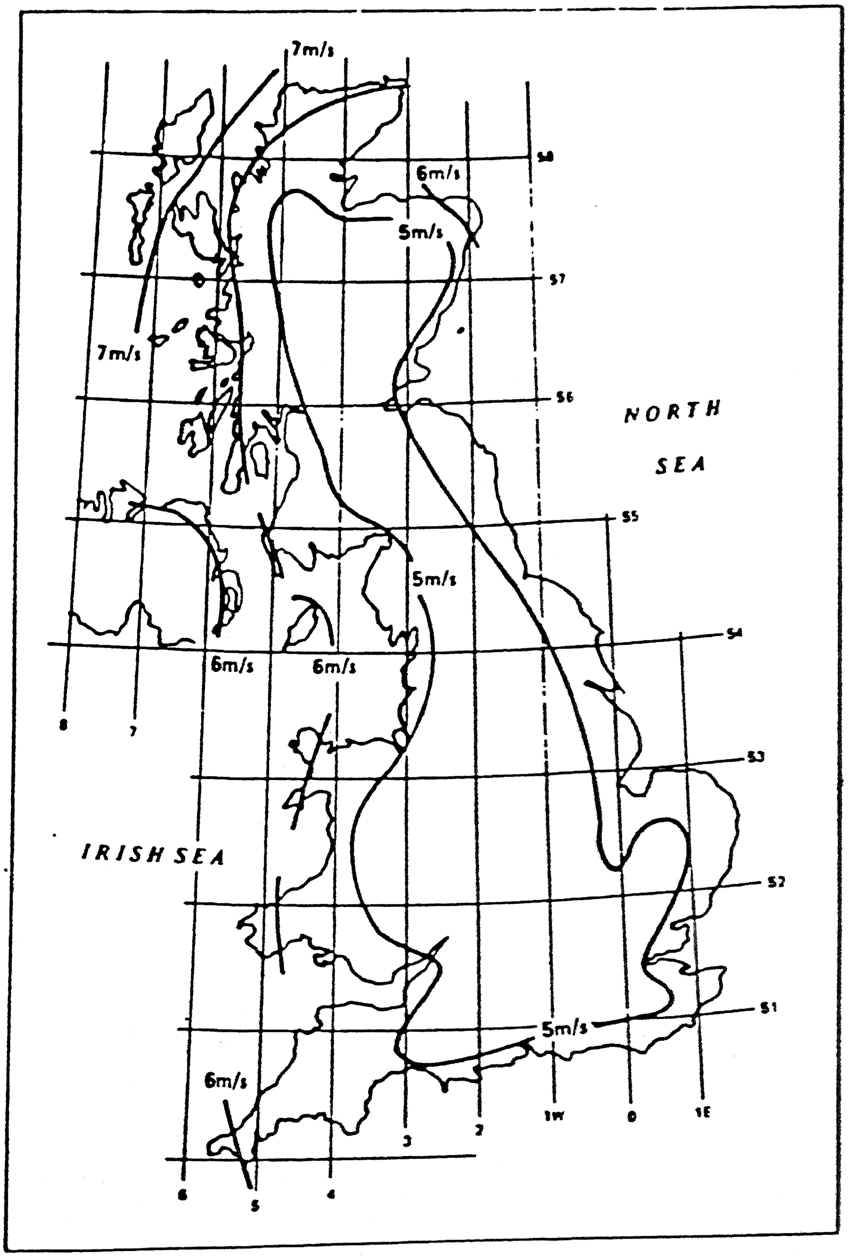


FIG. 2(a) 10 m Isovent Map of UNITED KINGDOM (ref. 25)

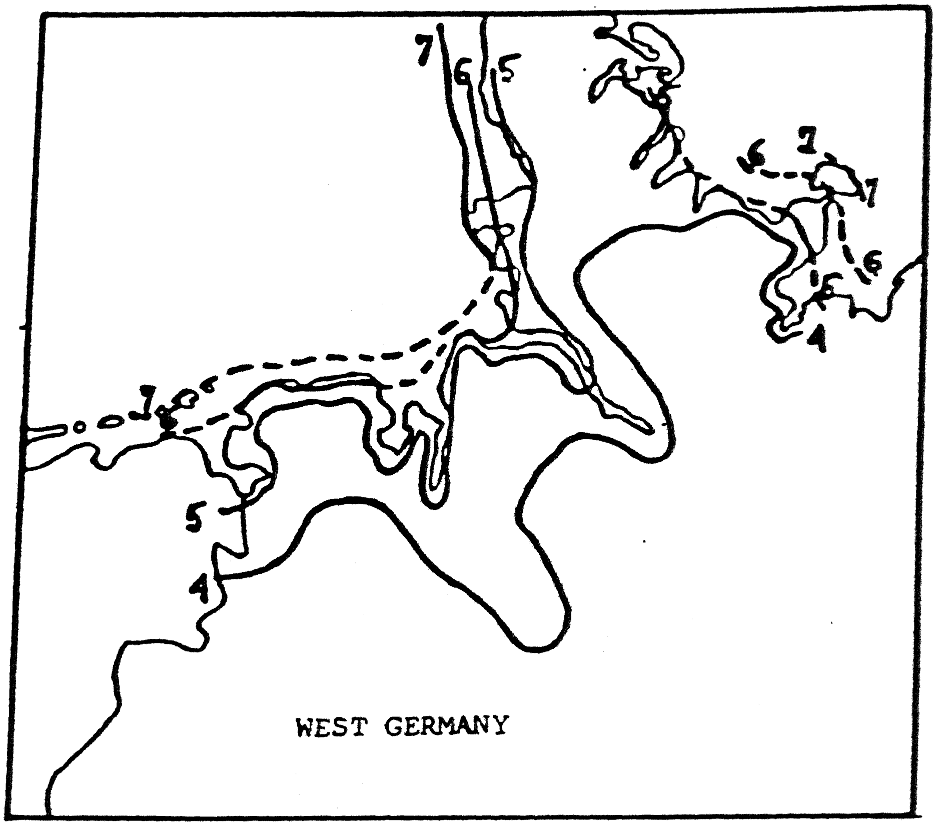


FIG. 2(b) 10 m Isovent Map of WEST GERMANY (Ref. 25)

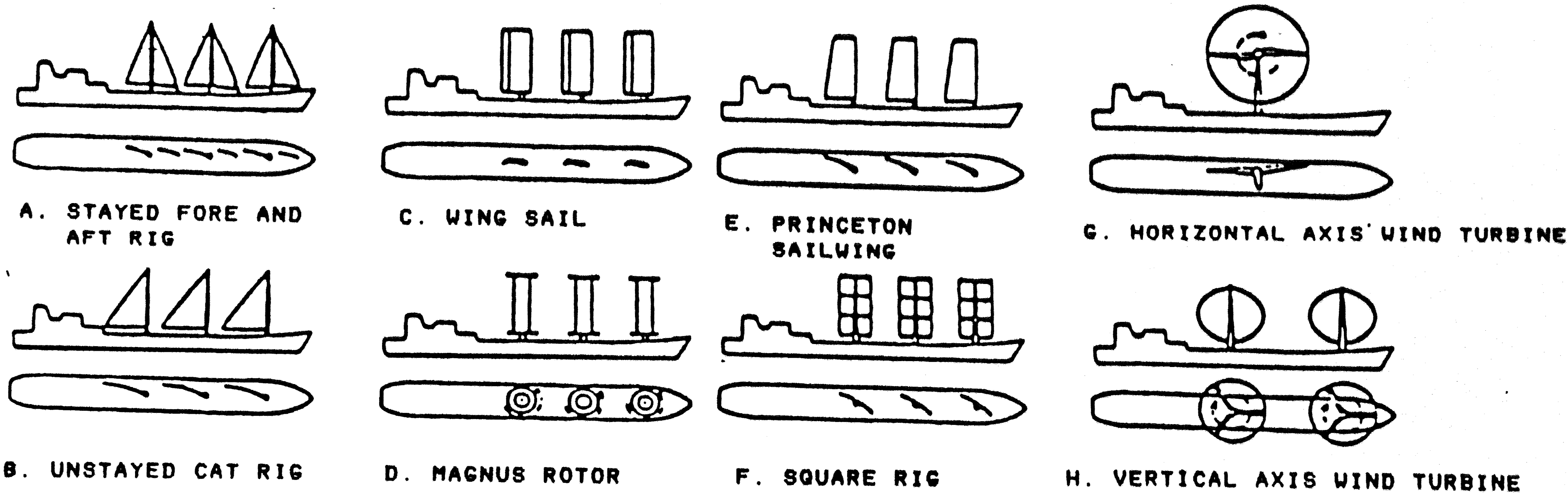


Fig. 3(a) VARIOUS SAIL RIGS (Ref. 7)

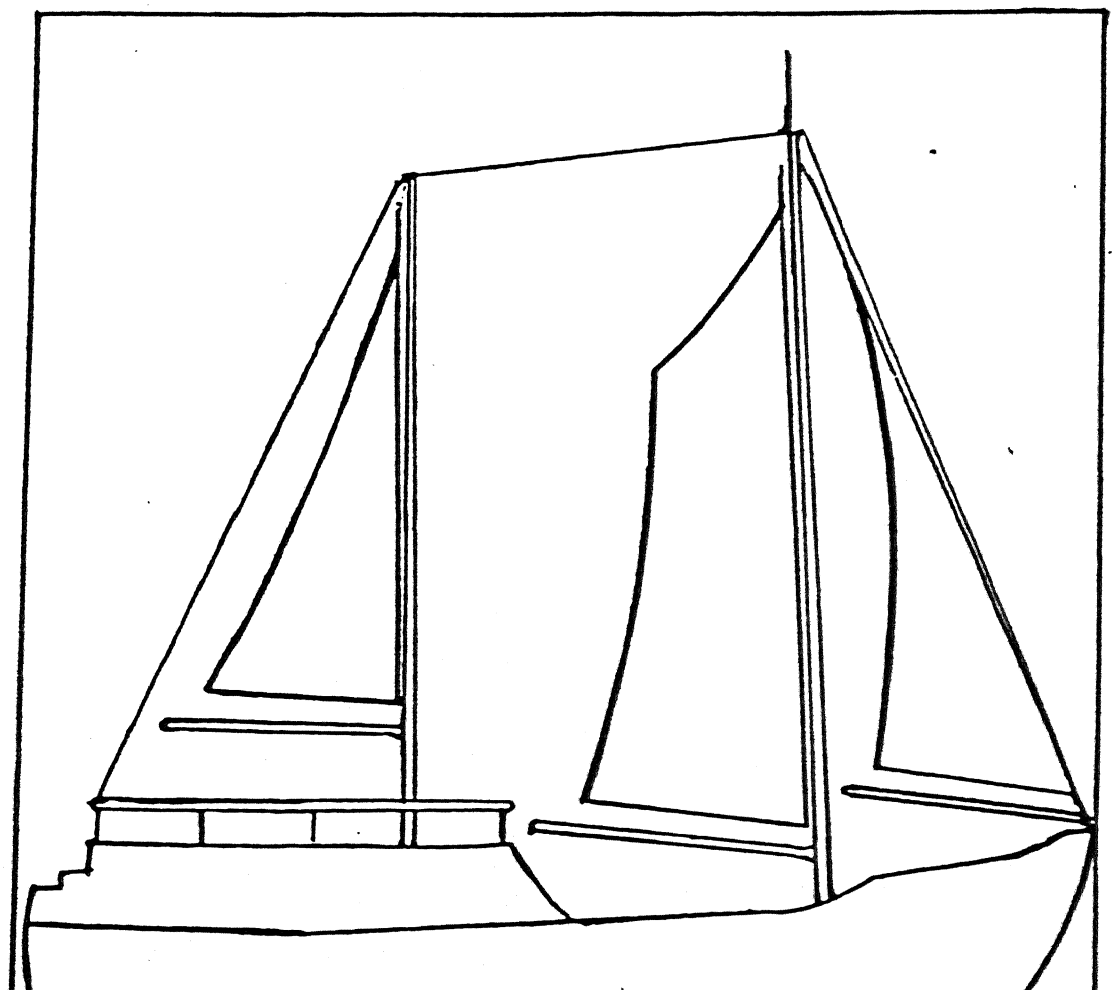
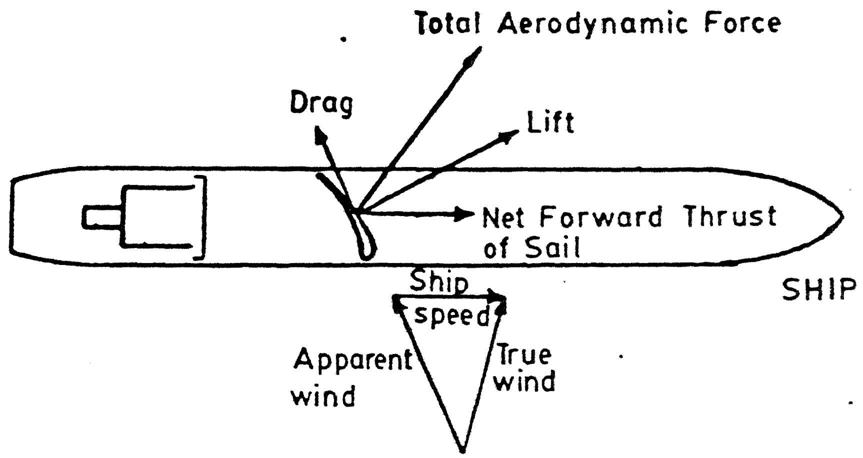
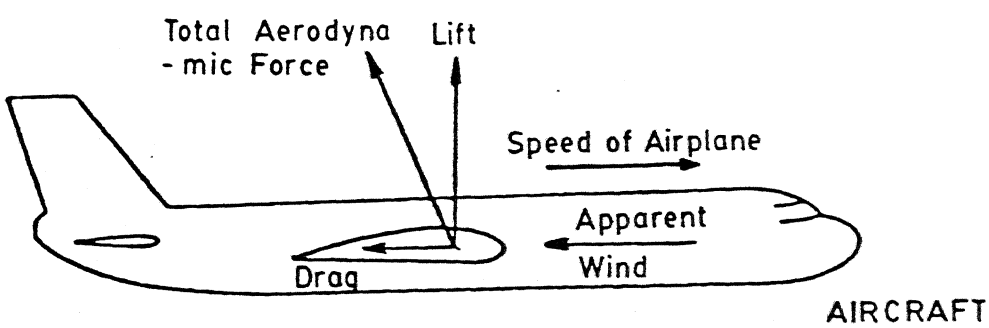


Fig. 3(b) COMBINATION OF CAT RIG AND GAFF SAIL USED IN FIJI ISLANDS EXPERIMENT (LINE DIAGRAM PREPARED FROM PHOTOGRAPH, REF. 17)



(a)



(b)

FIG. 4 AERODYNAMIC FORCES AND COMPONENTS (ref. 7)

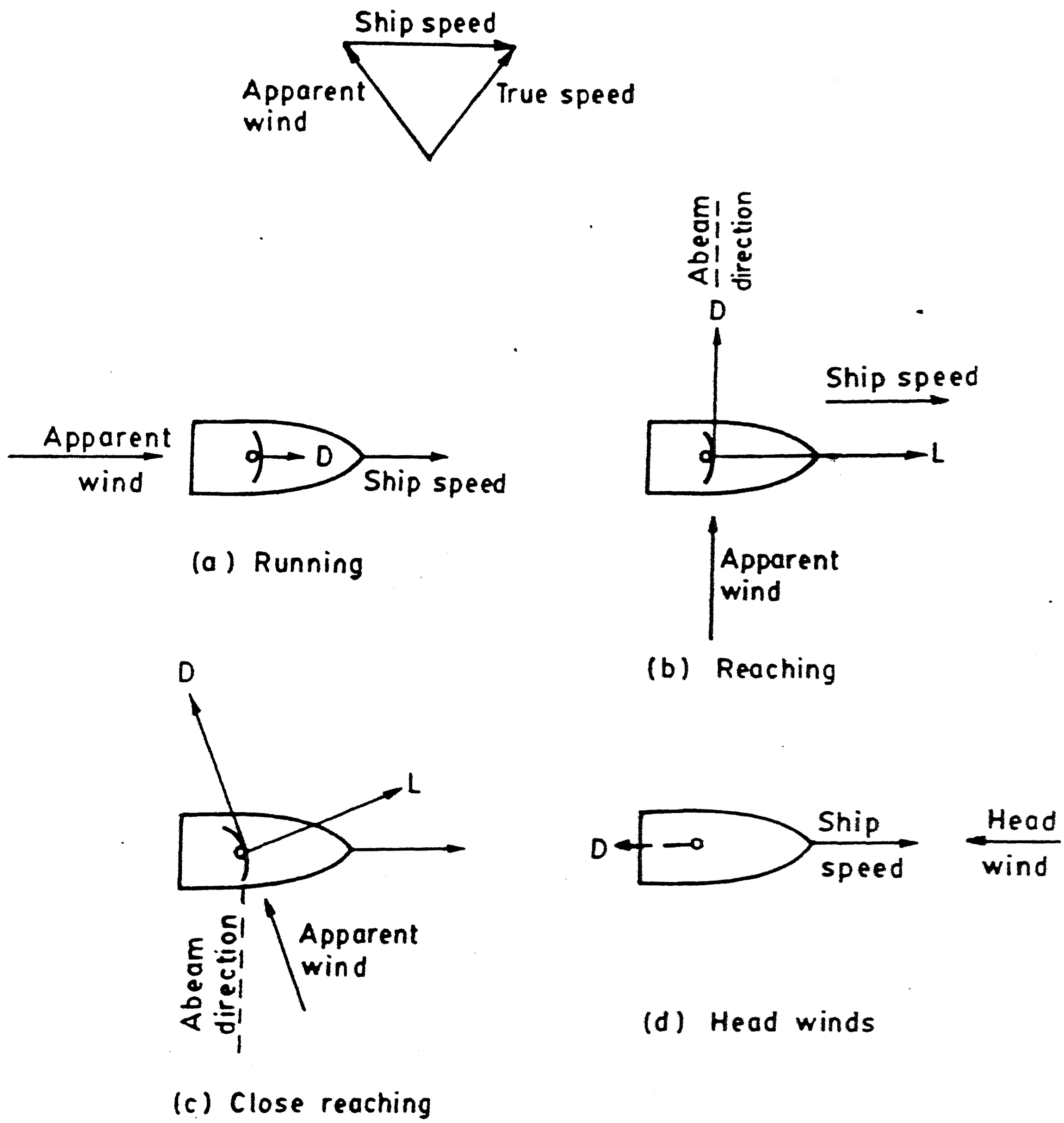


FIG. 5 DIFFERENT MODES OF SAILING ; L ,D DENOTE LIFT AND DRAG FORCES

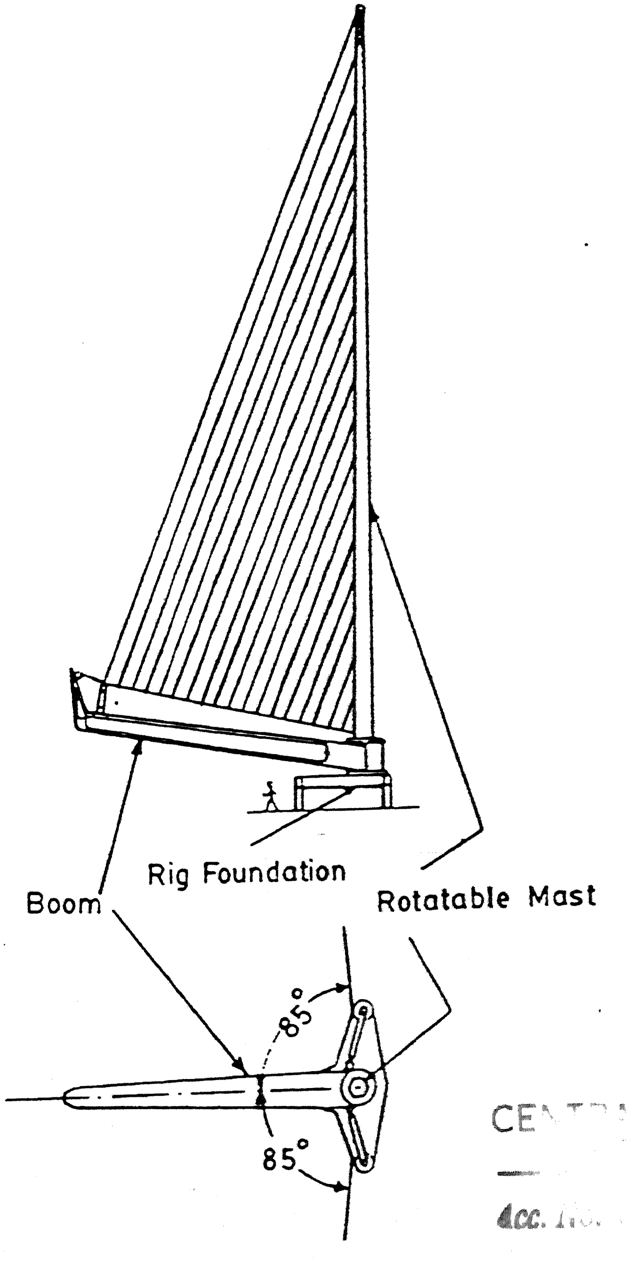


FIG. 6 CAT RIG : GENERAL ARRANGEMENT [ref. 7]

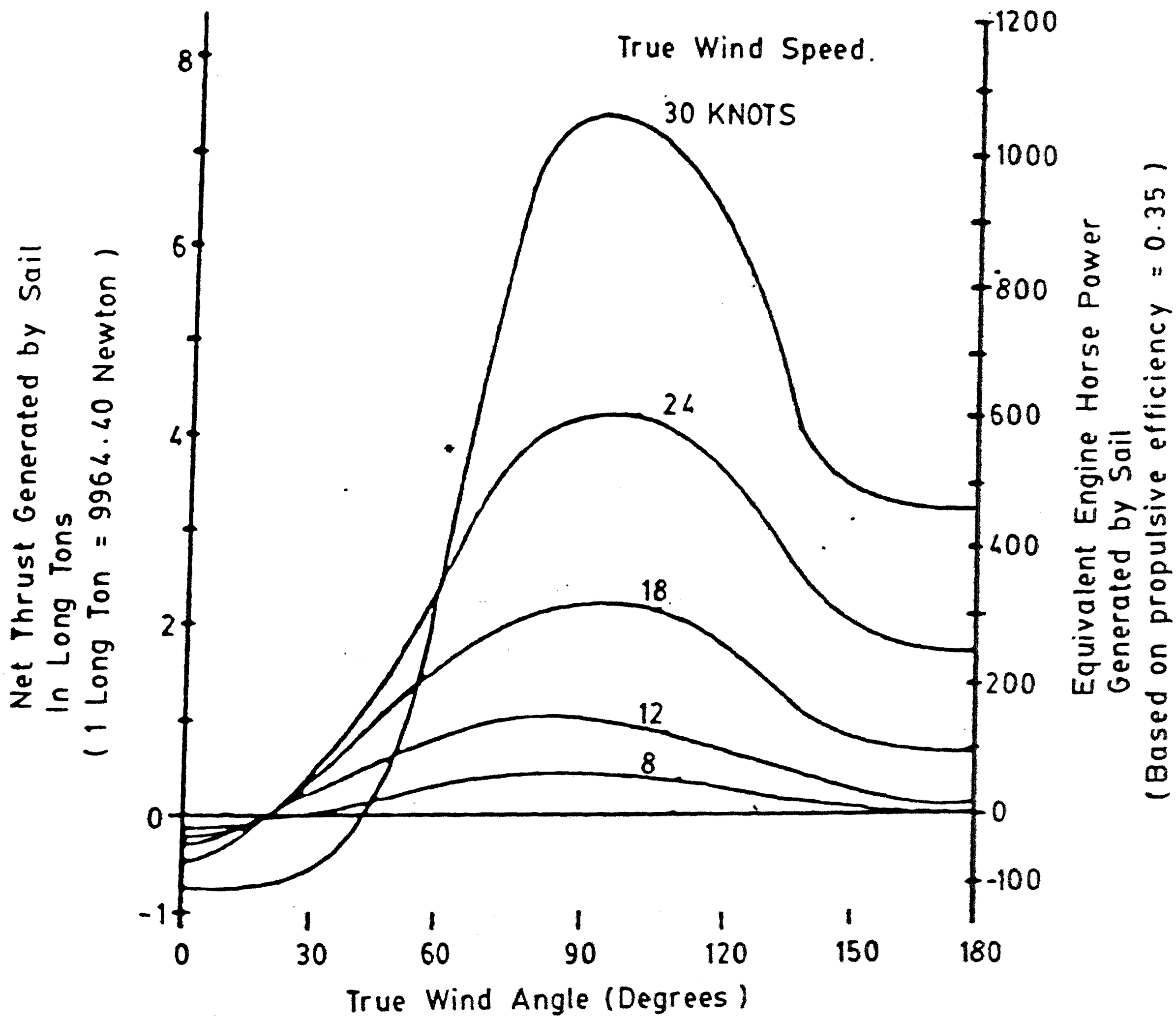


FIG. 7 HORSE POWER AND THRUST OF 3000 Sq. Ft (= 278.70 m^2) CAT RIG. (Ref. 7)
SHIP SPEED = 7 KNOTS (12.96 KMPH)

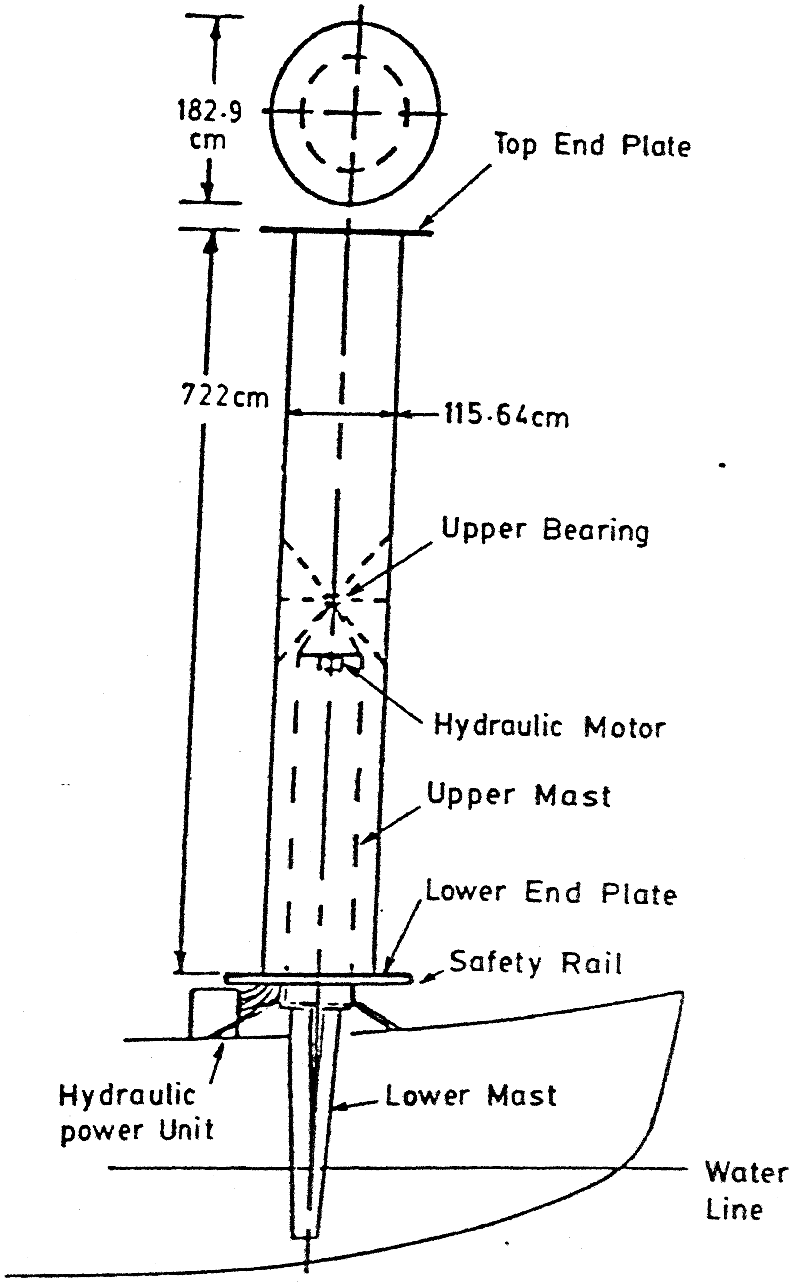


FIG. 8 EXPERIMENTAL MAGNUS ROTOR: GENERAL ARRANGEMENT (Ref. 7)

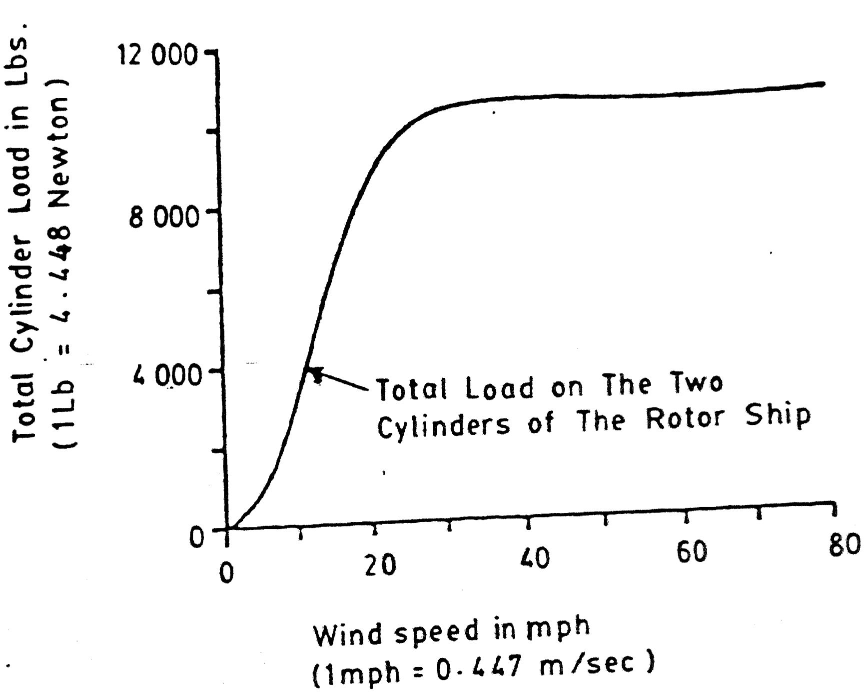


FIG. 9 MEASURED LOAD ON MAGNUS ROTOR Vs. WIND SPEED (Ref .7)

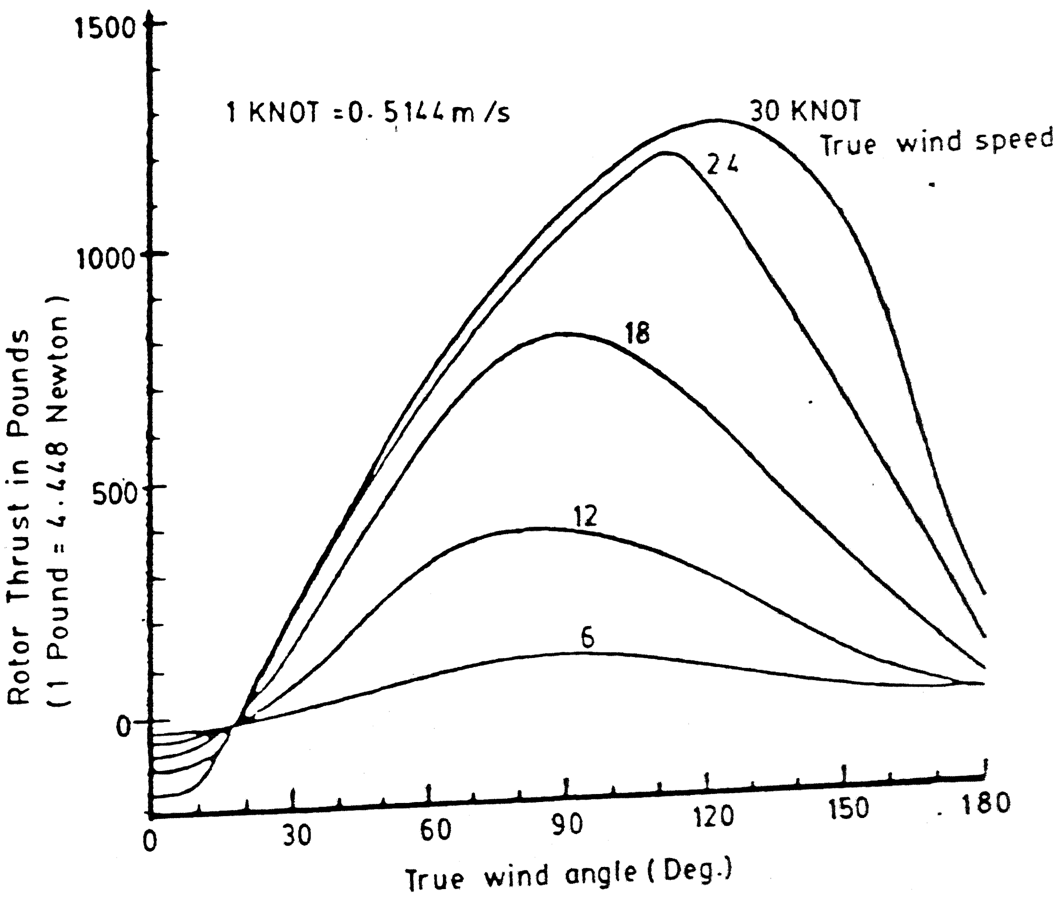


FIG. 10 PROPULSIVE FORCE SUPPLIED BY 90 FT^2 (=8.36 m^2) MAGNUS ROTOR (Ref.7)

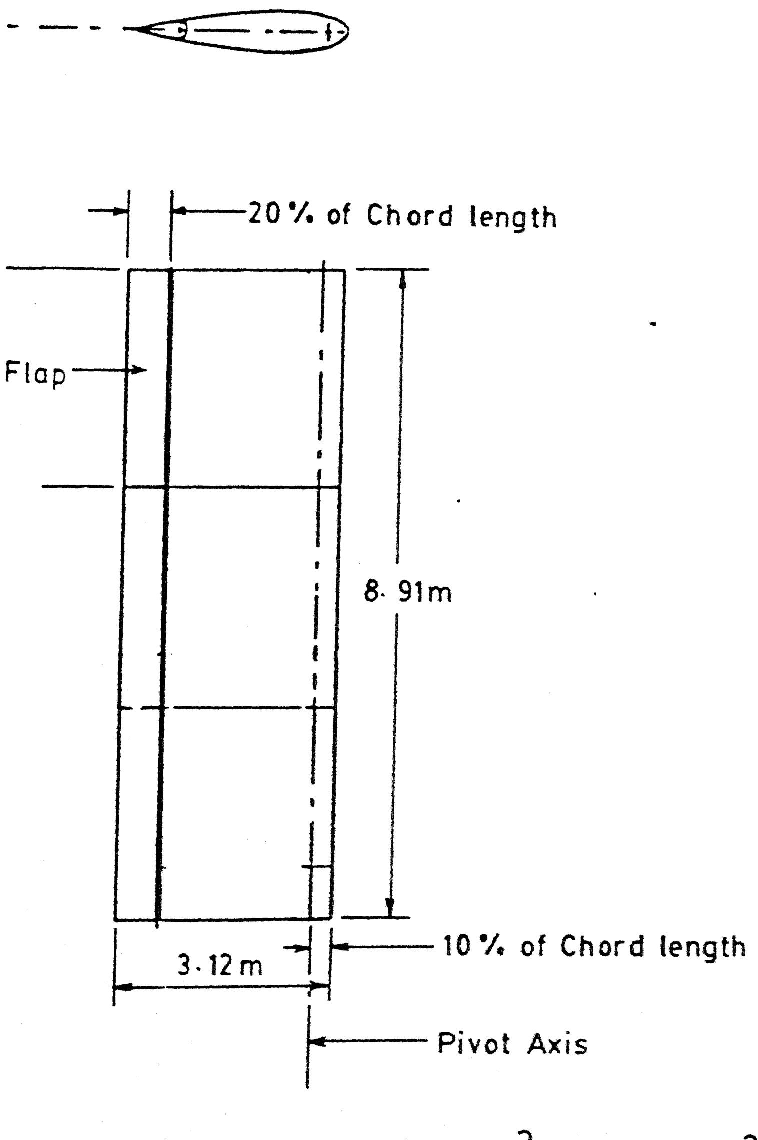


FIG. 11 GENERAL ARRANGEMENT OF 300 FT^2 (= 27·87 m^2) WINGSAIL TEST RIG; NACA 0018 AIRFOIL SECTION (Ref. 7)

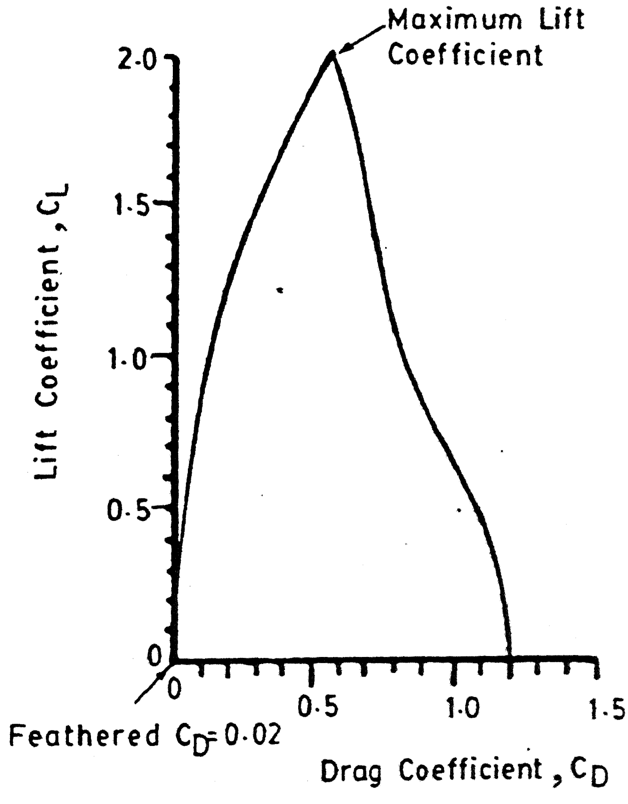


FIG. 12 300 FT^2 (= 27.87 m^2) WING SAIL MODEL LIFT / DRAG POLAR (Ref. 7)

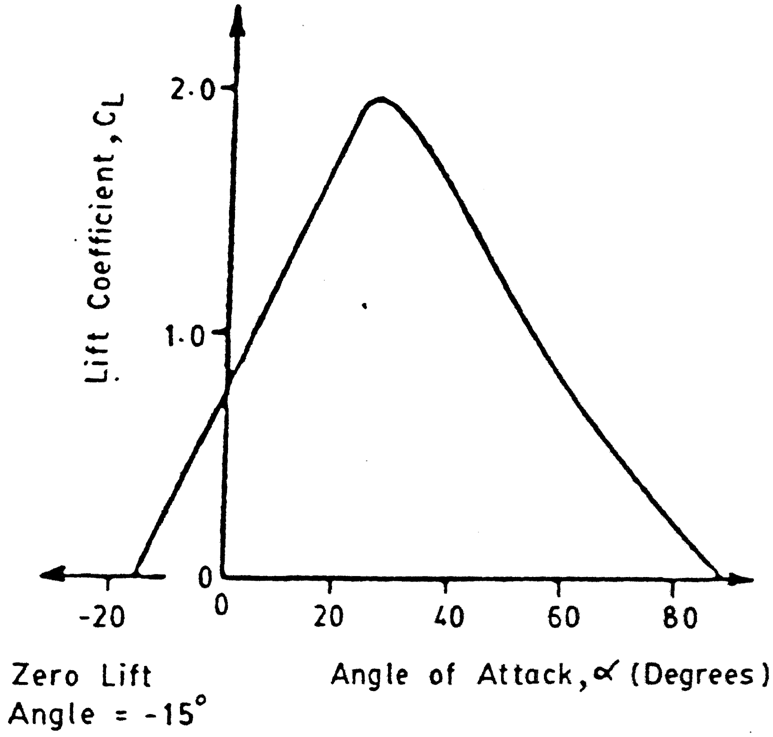


FIG. 13 LIFT CURVE FOR 300 FT^2 (= 27.87 m^2) WING SAIL; WITH FLAP DEFLECTION 45° (Ref.7)

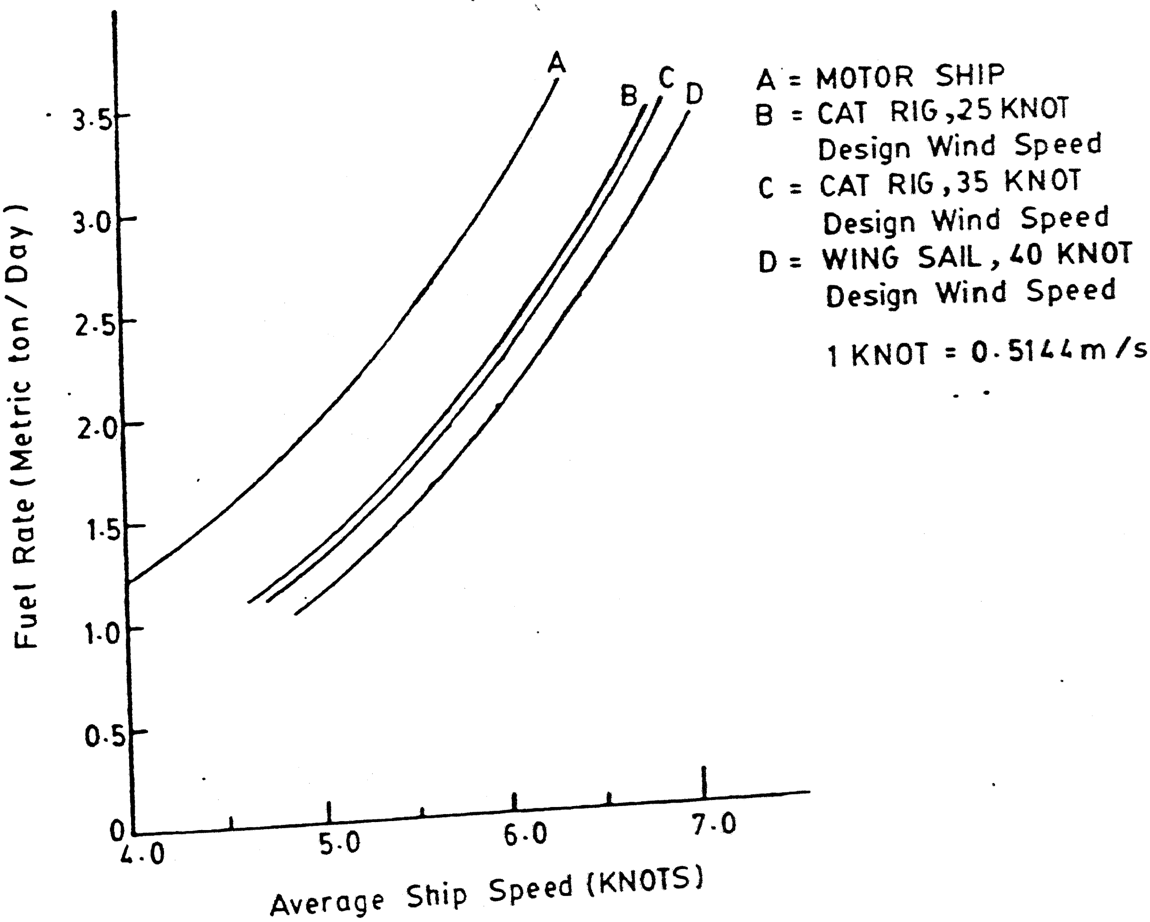


FIG. 14 MINI LACE MAIN ENGINE FUEL CONSUMPTION WITH VARIOUS SAIL TYPES AND DESIGN WIND SPEEDS (Ref. 7)

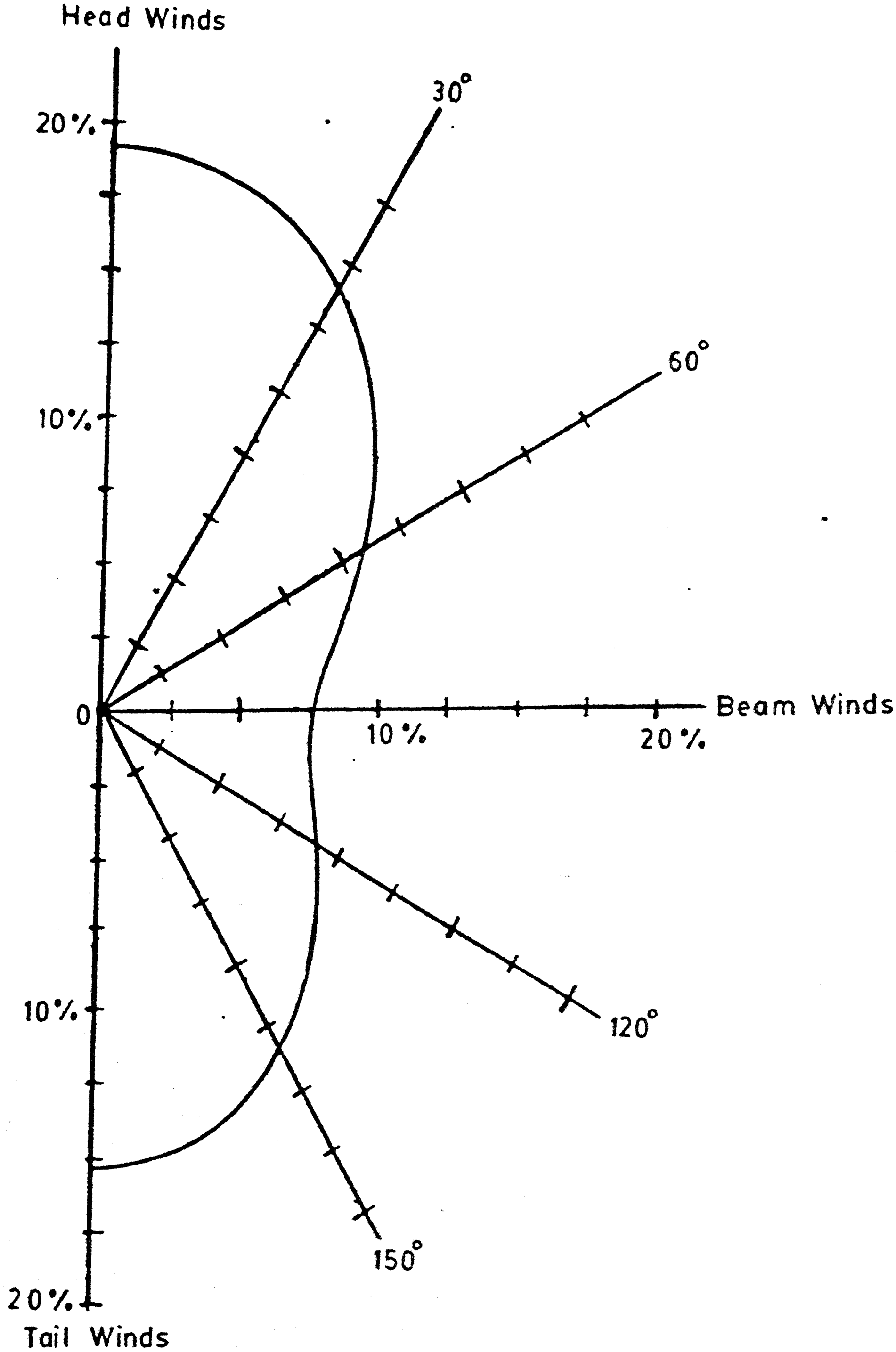


FIG. 15(a) WIND DISTRIBUTION RECORDED ON MINI-LACE FOR THE TEST JOURNEY (Ref.7)

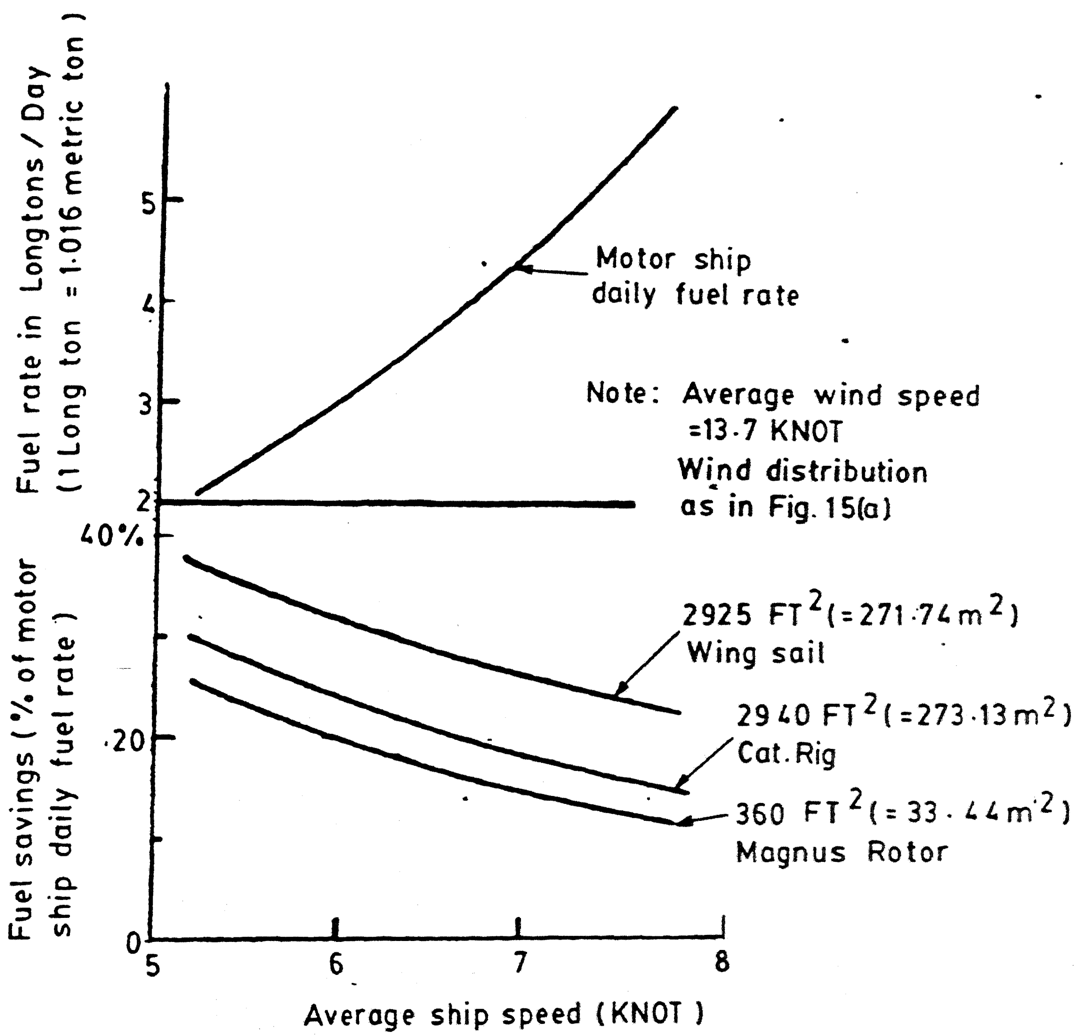
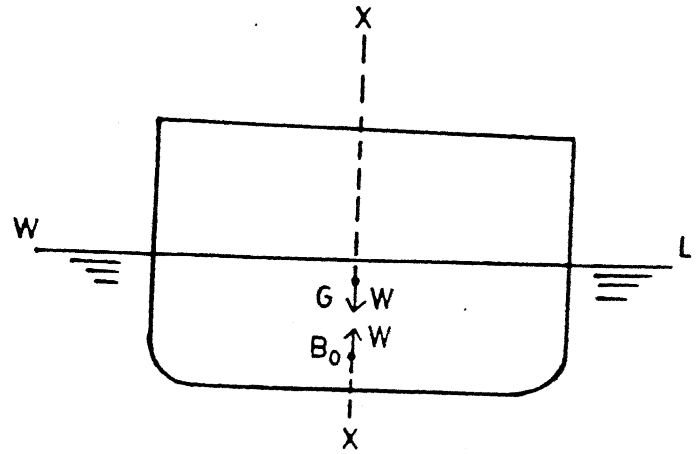
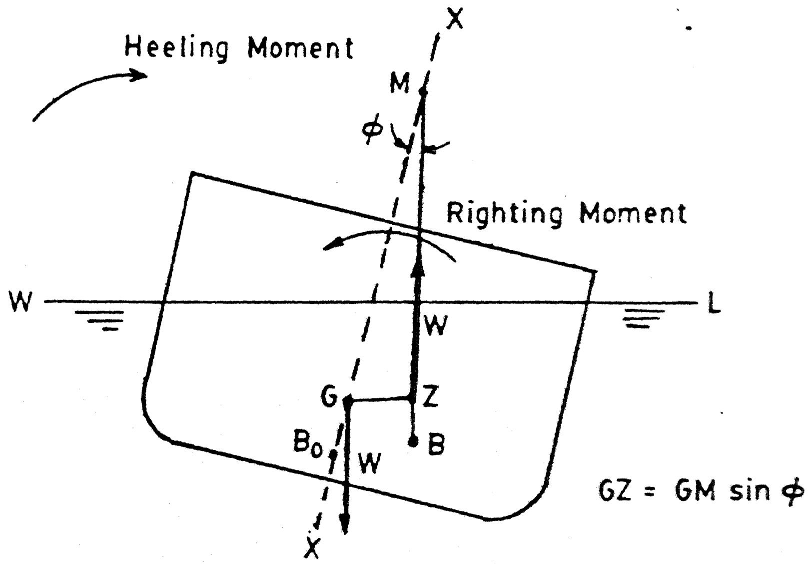


FIG. 15(b) MINI-SHIP FUEL CONSUMPTION WITH VARIOUS RIGS. OF SAME EQIVALENT AREA (Ref.7)



(a)



(b)

FIG. 16 ACTION OF BUOYANCY FORCE AND WEIGHT (Ref. 21)

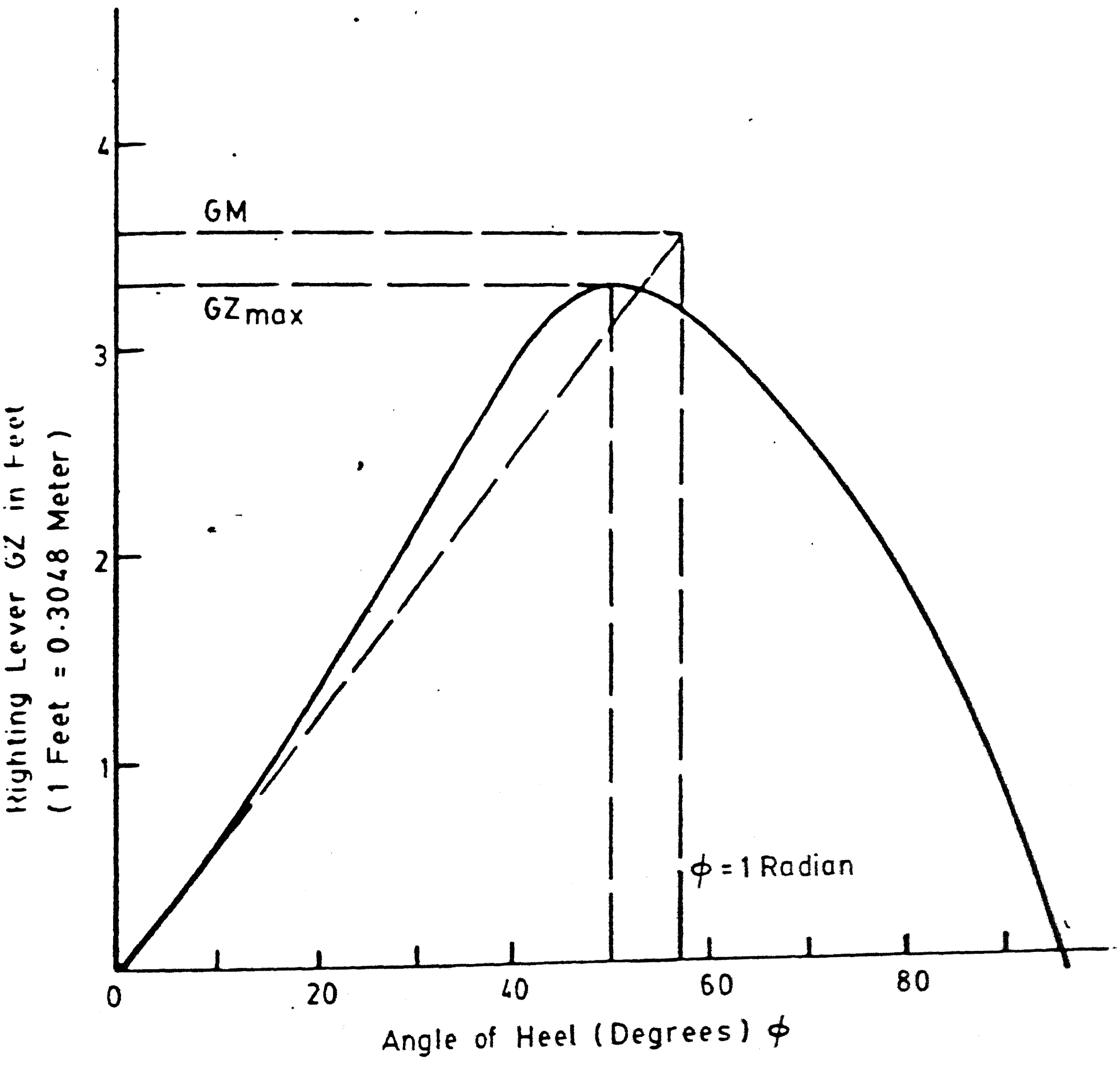


FIG. 17 CURVE OF STATICAL STABILITY (Ref. 21)

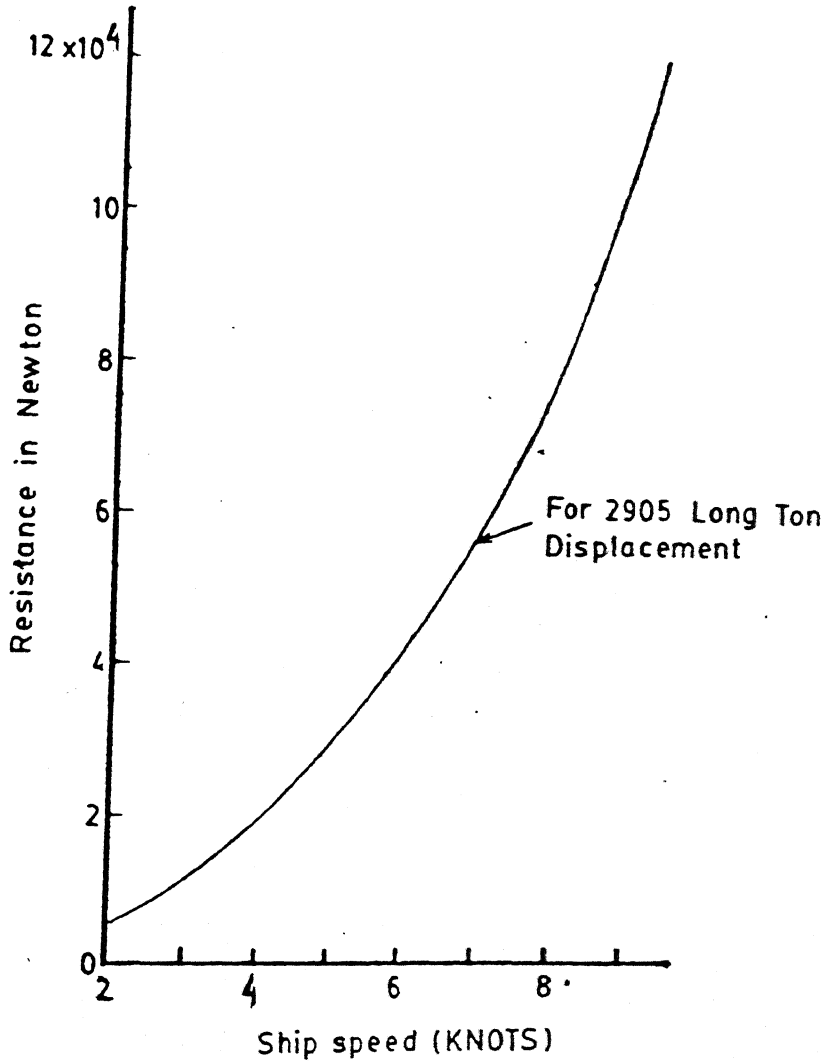
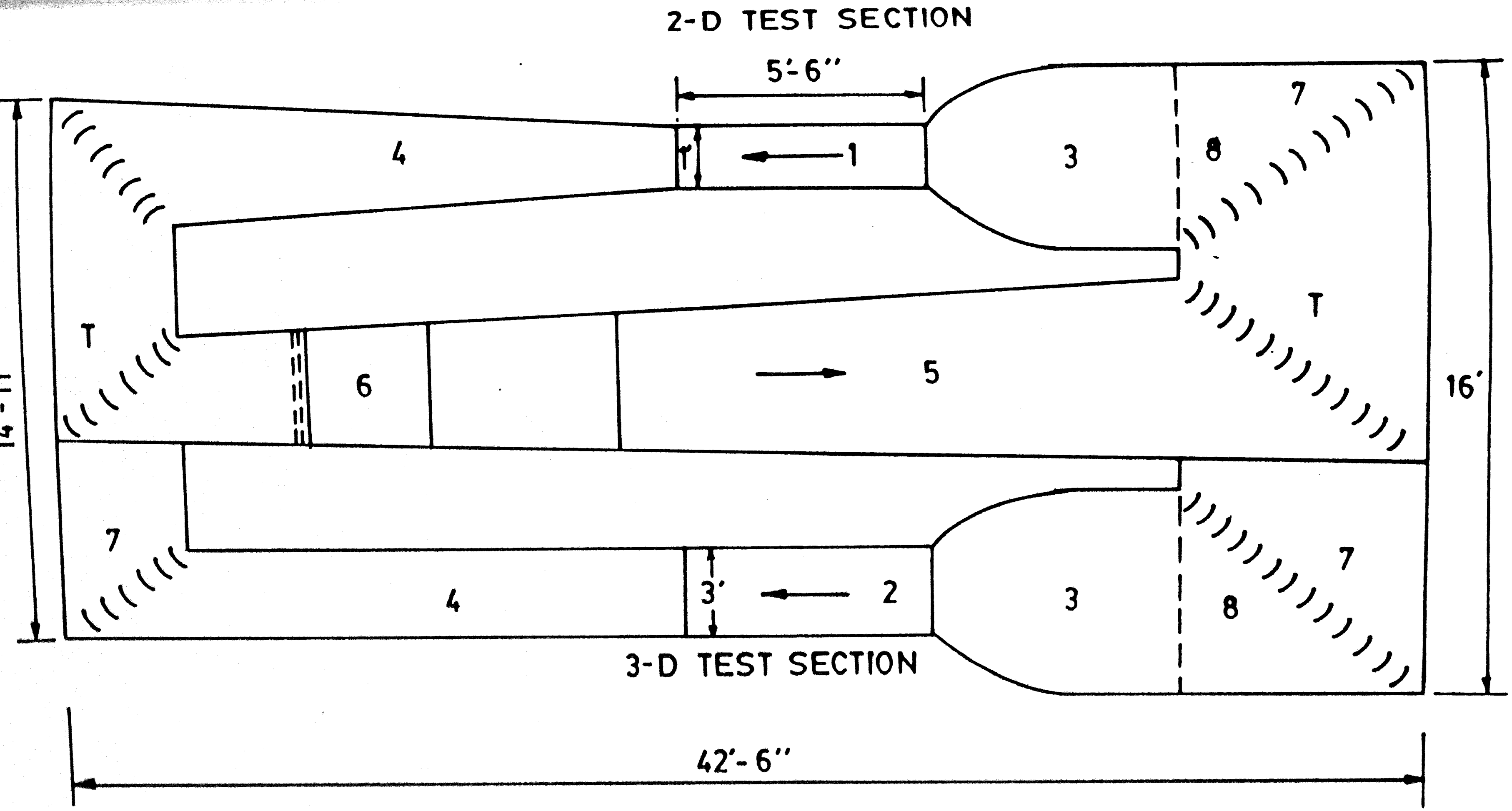


FIG. 18 RESISTANCE CURVE FOR MINILACE FOR 2905 LONGTON (2951·48 metric ton) [Ref. 7]



1. 2 - D TEST SECTION (5'-6"x 1' x 4')
2. 3 - D TEST SECTION (5'-6"x 3'x 2')
3. CONTRACTION CONE
4. DIFFUSER
5. RETURN DIFFUSER
6. BLOWER SECTION (2-12 Blade-15 H.P. Fan)
7. TURNING VANES
8. SCREENS
T. TURNING BOX

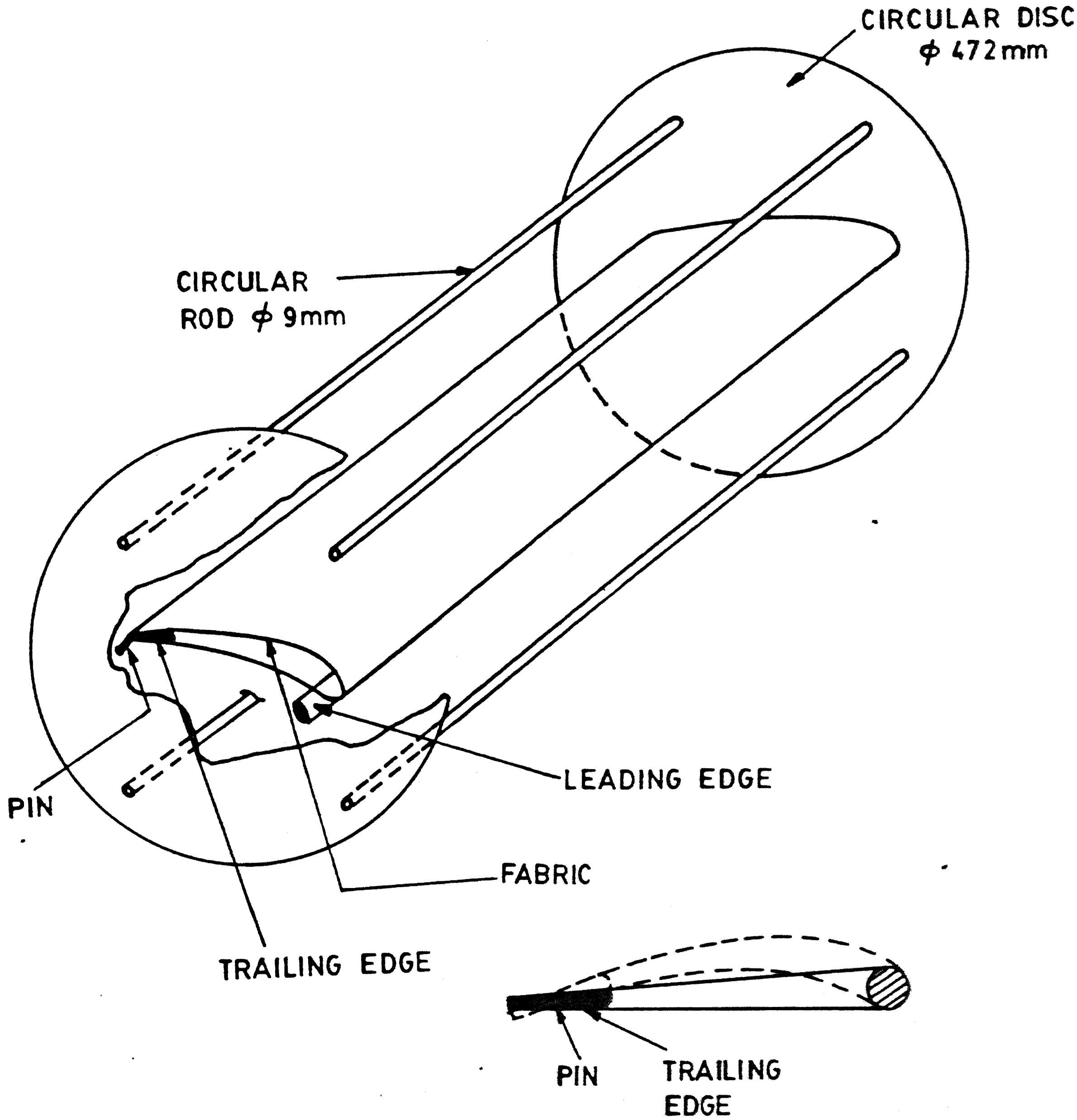


FIG. 20 SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SET UP

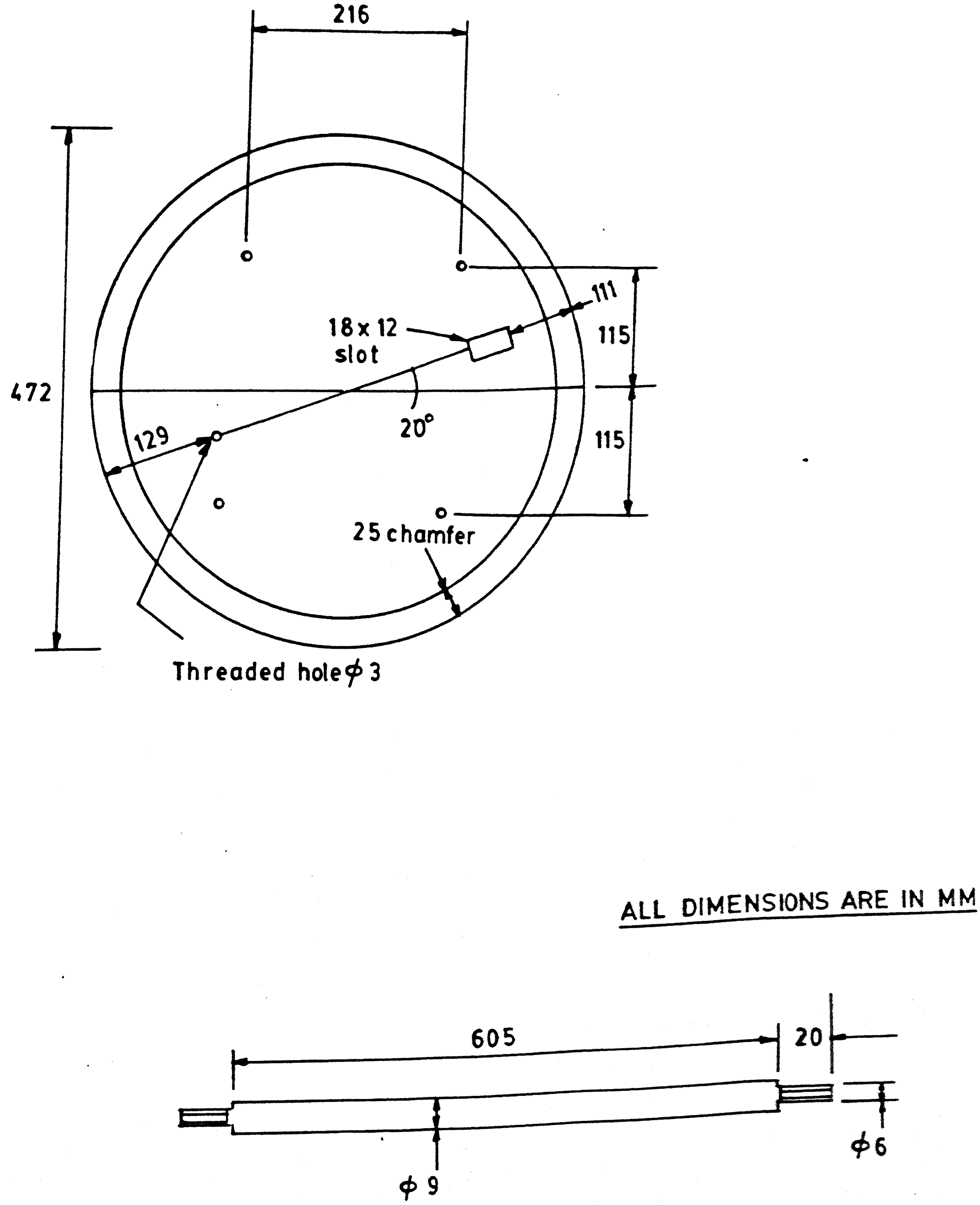
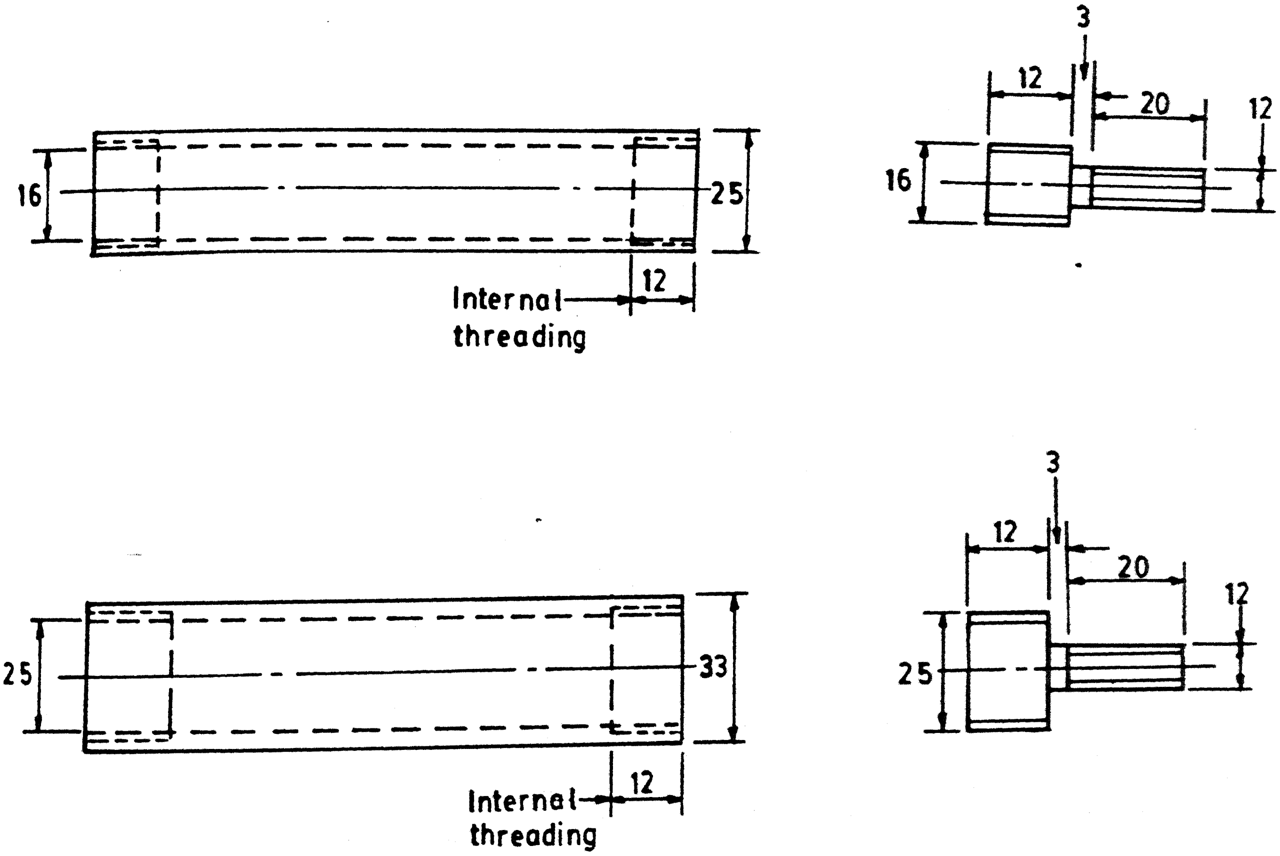
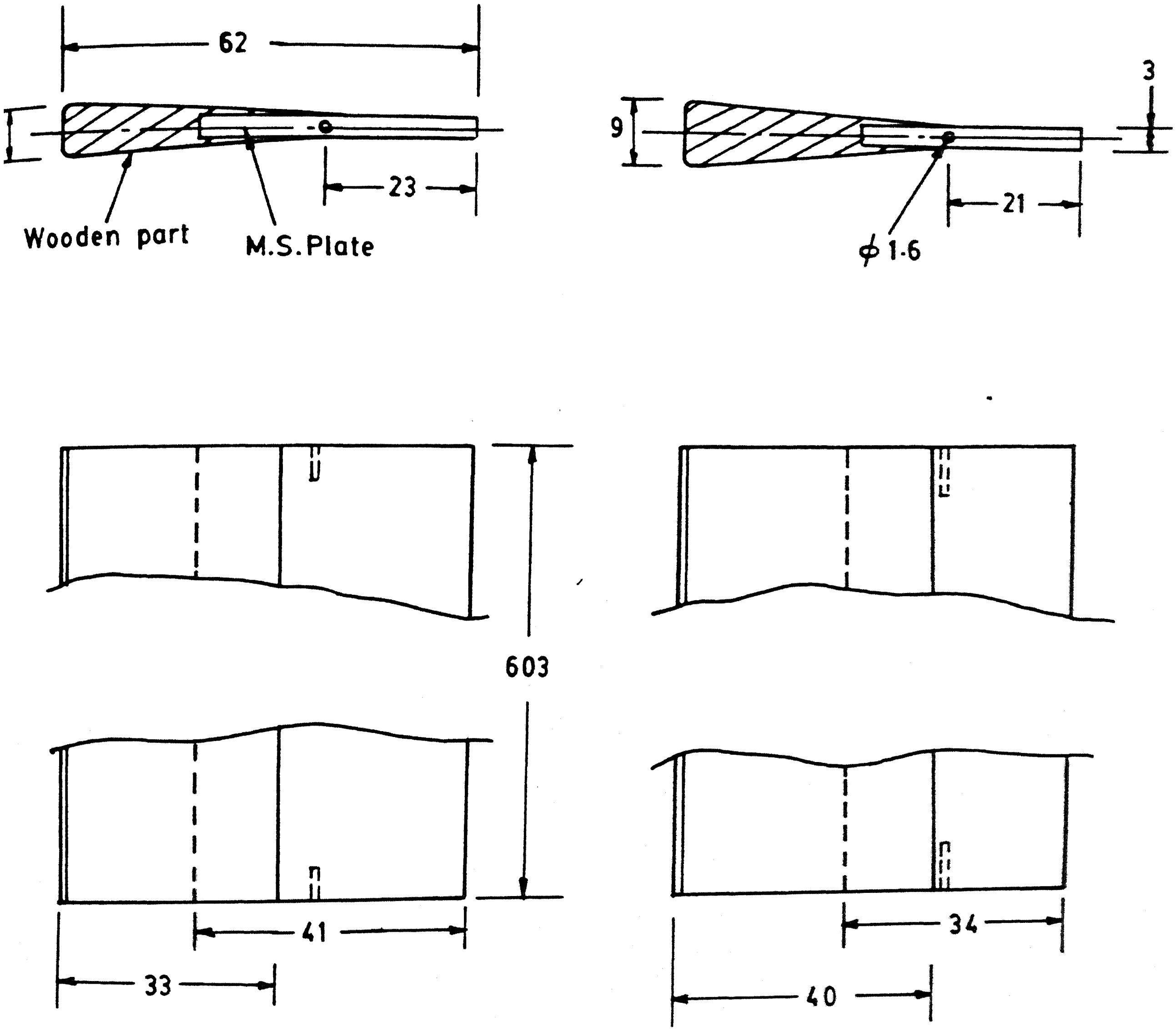


FIG. 21 CIRCULAR DISC AND CIRCULAR ROD



ALL DIMENSIONS ARE IN MM

FIG. 22 LEADING EDGE PIPES



ALL DIMENSIONS ARE IN MM

FIG. 23 TRAILING EDGE PIECES

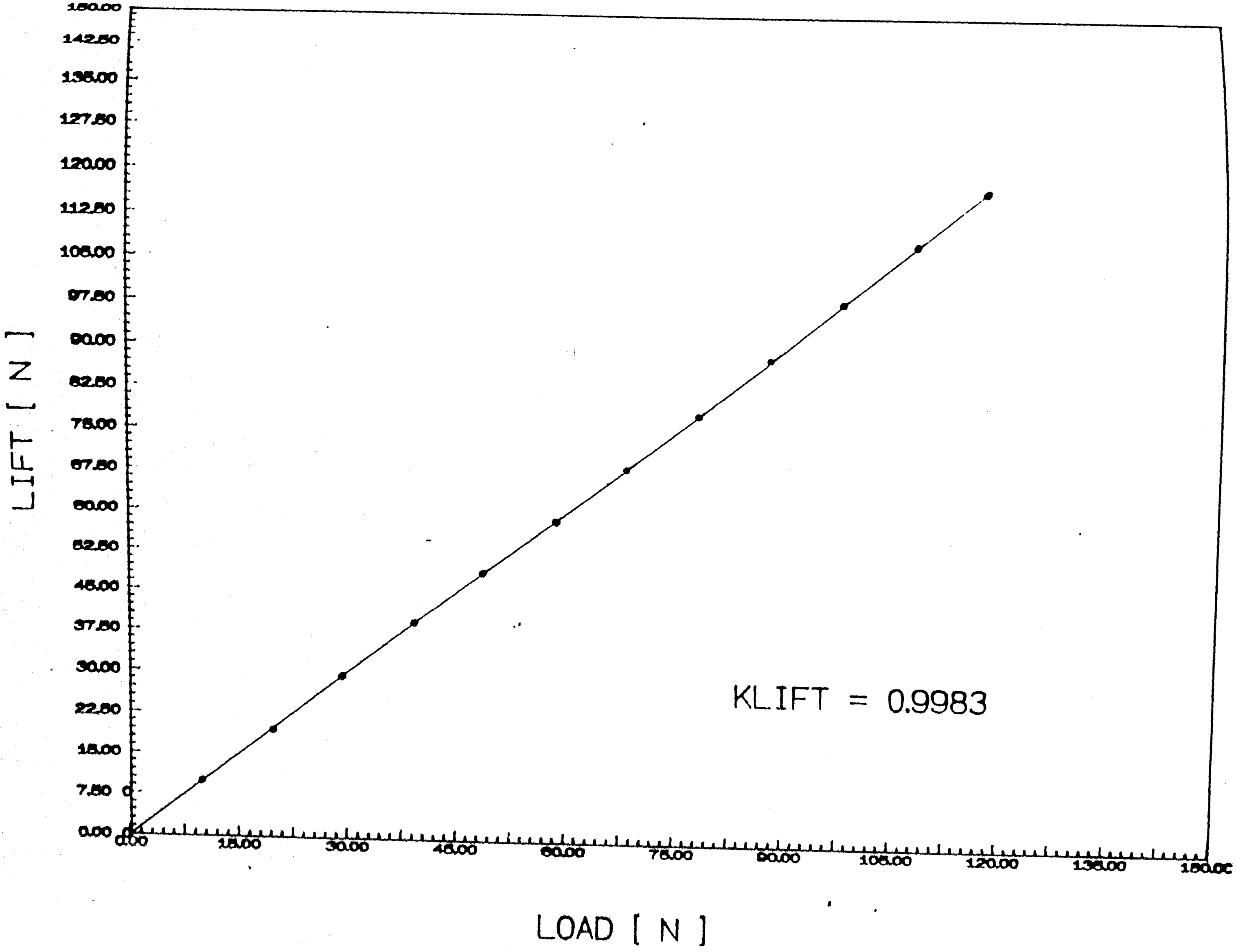


FIG.24 THREE COMPONENT BALANCE

CALIBRATION CURVE : LIFT

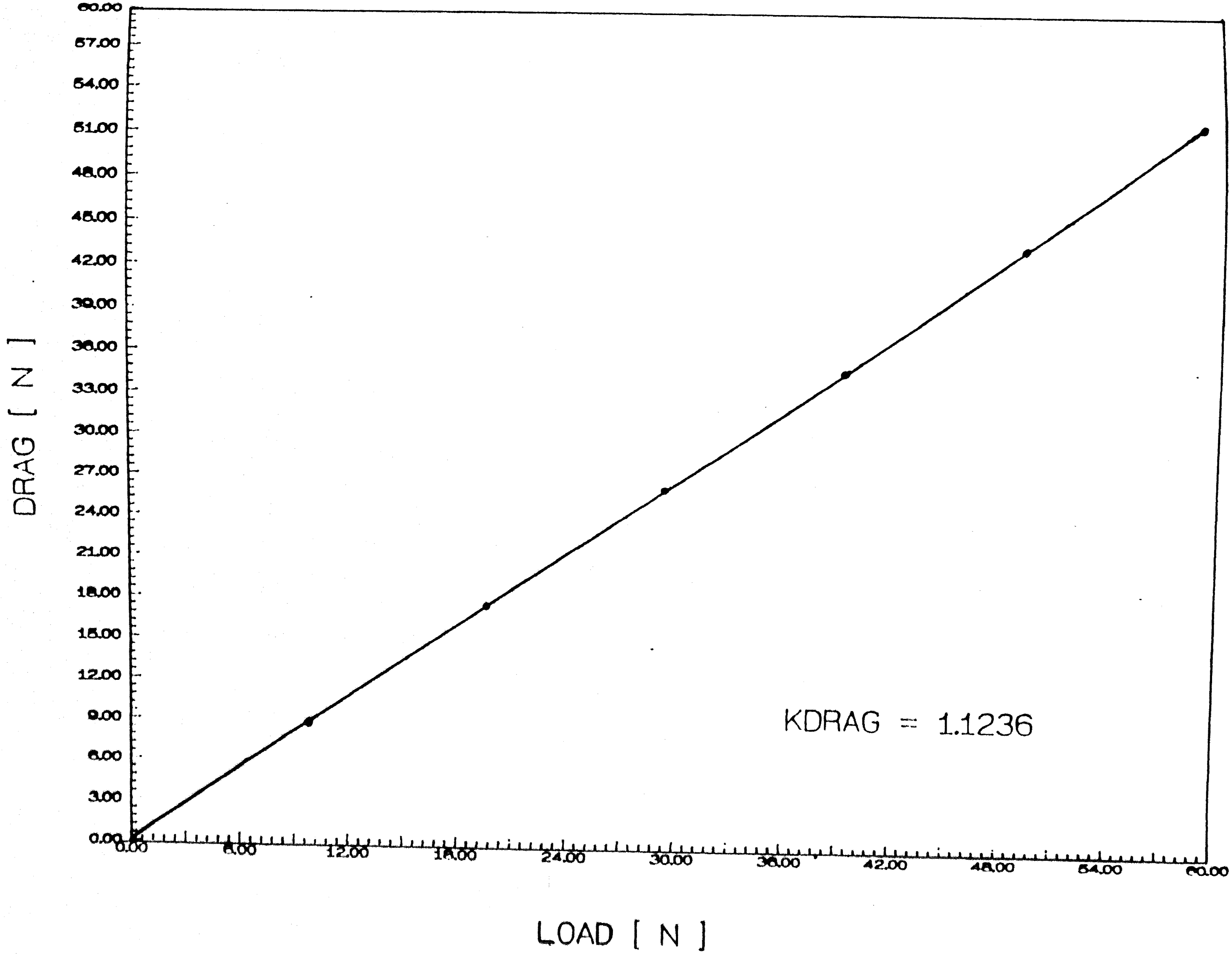


FIG.25 THREE COMPONENT BALANCE

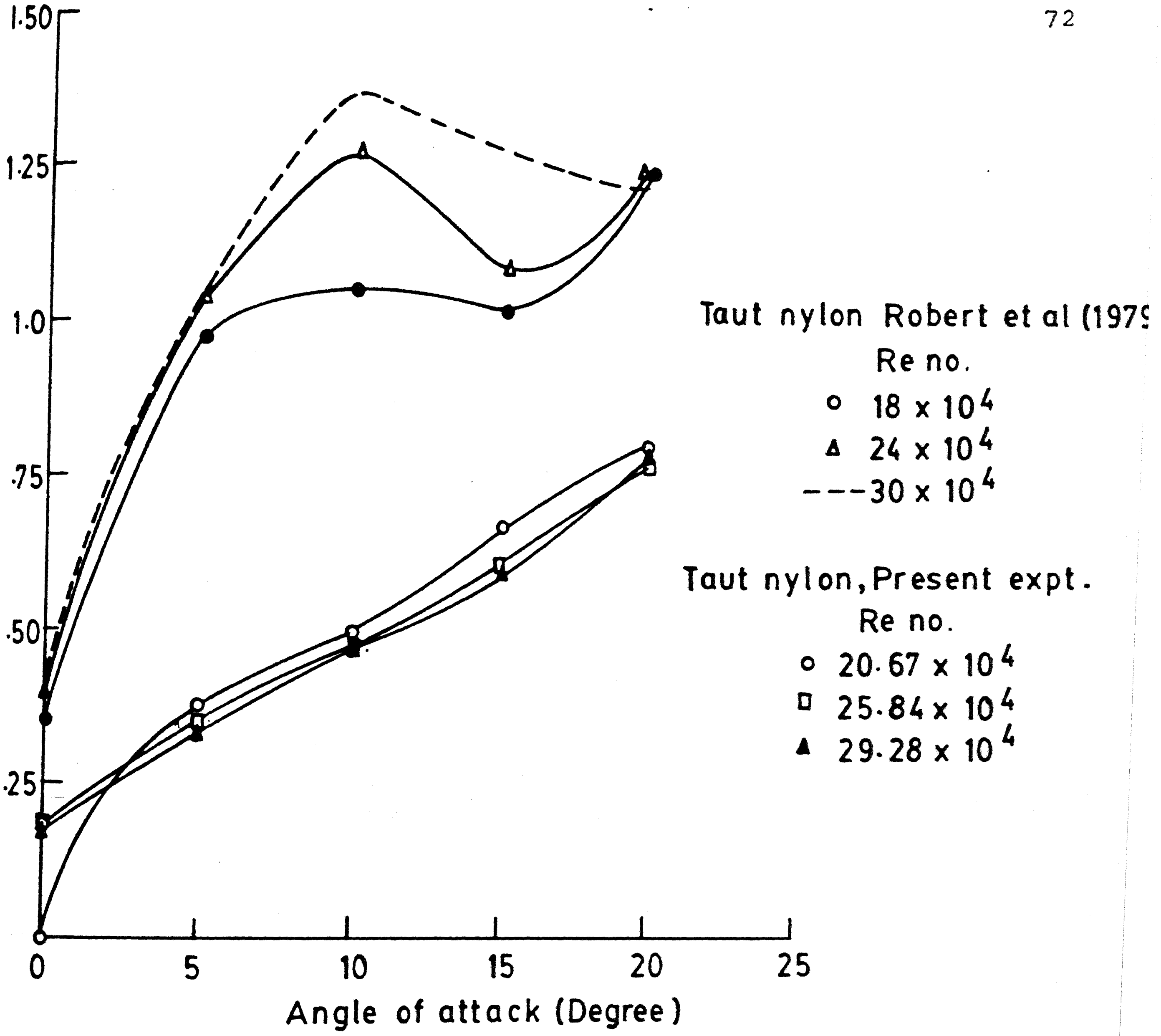
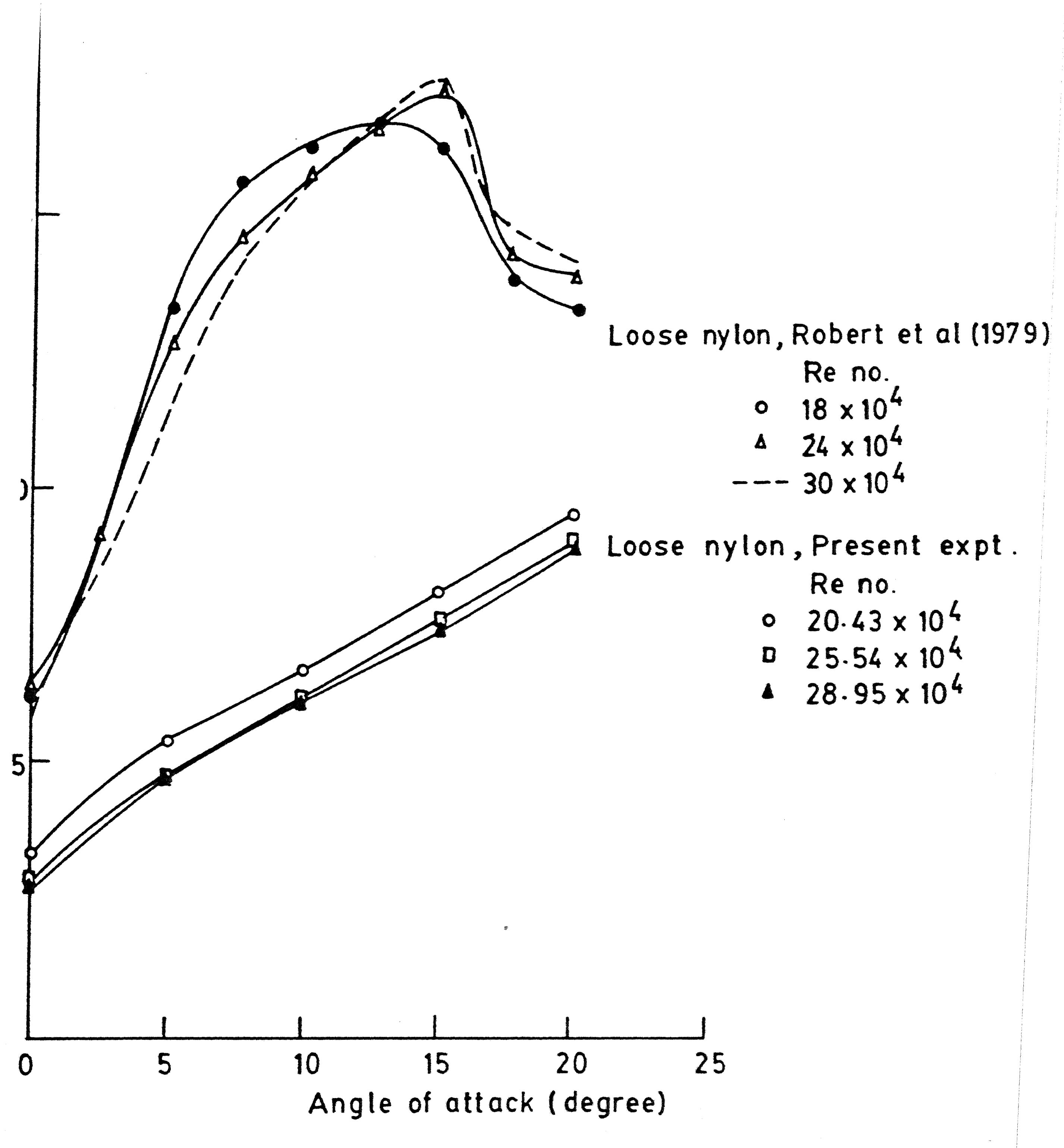
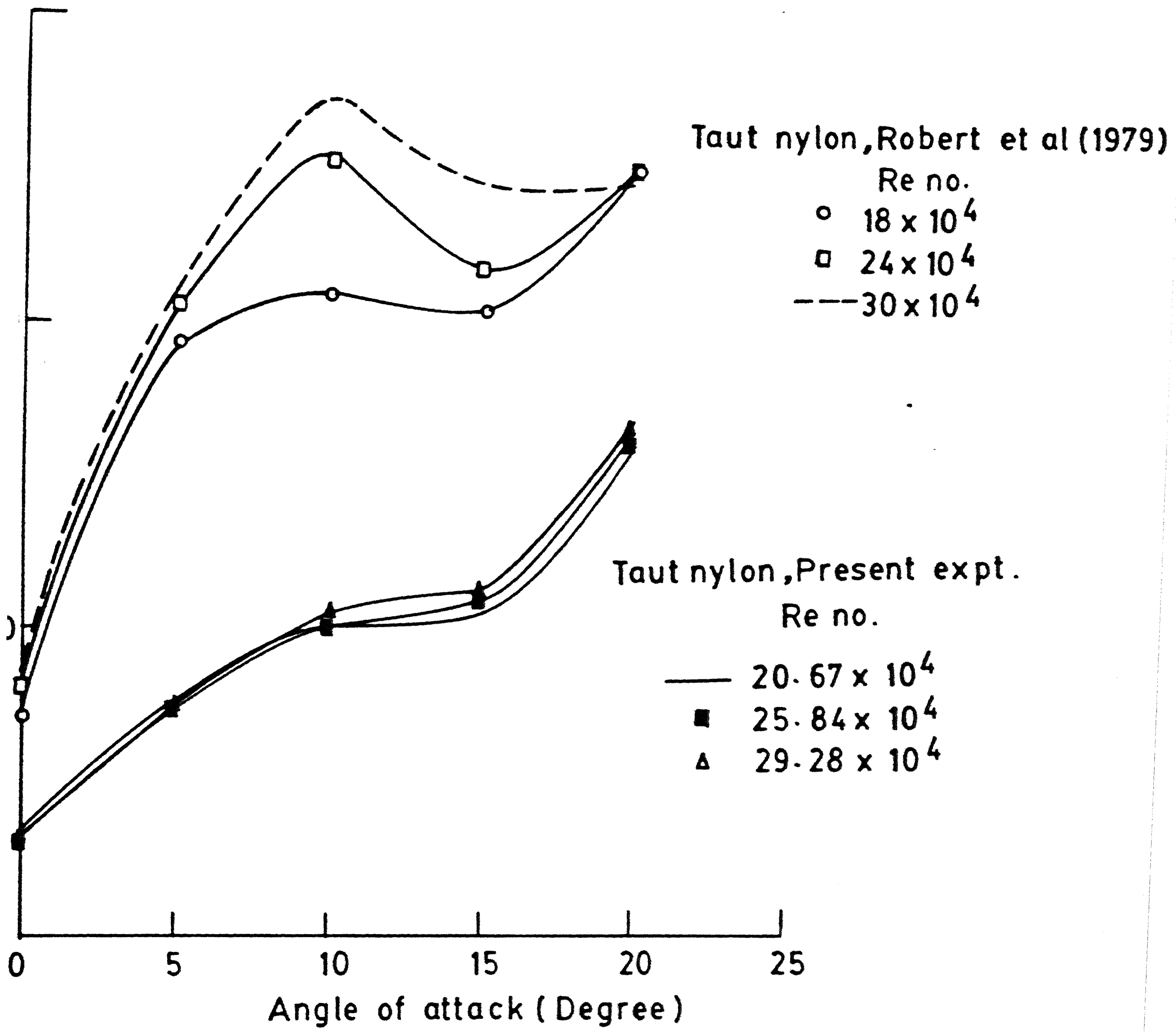


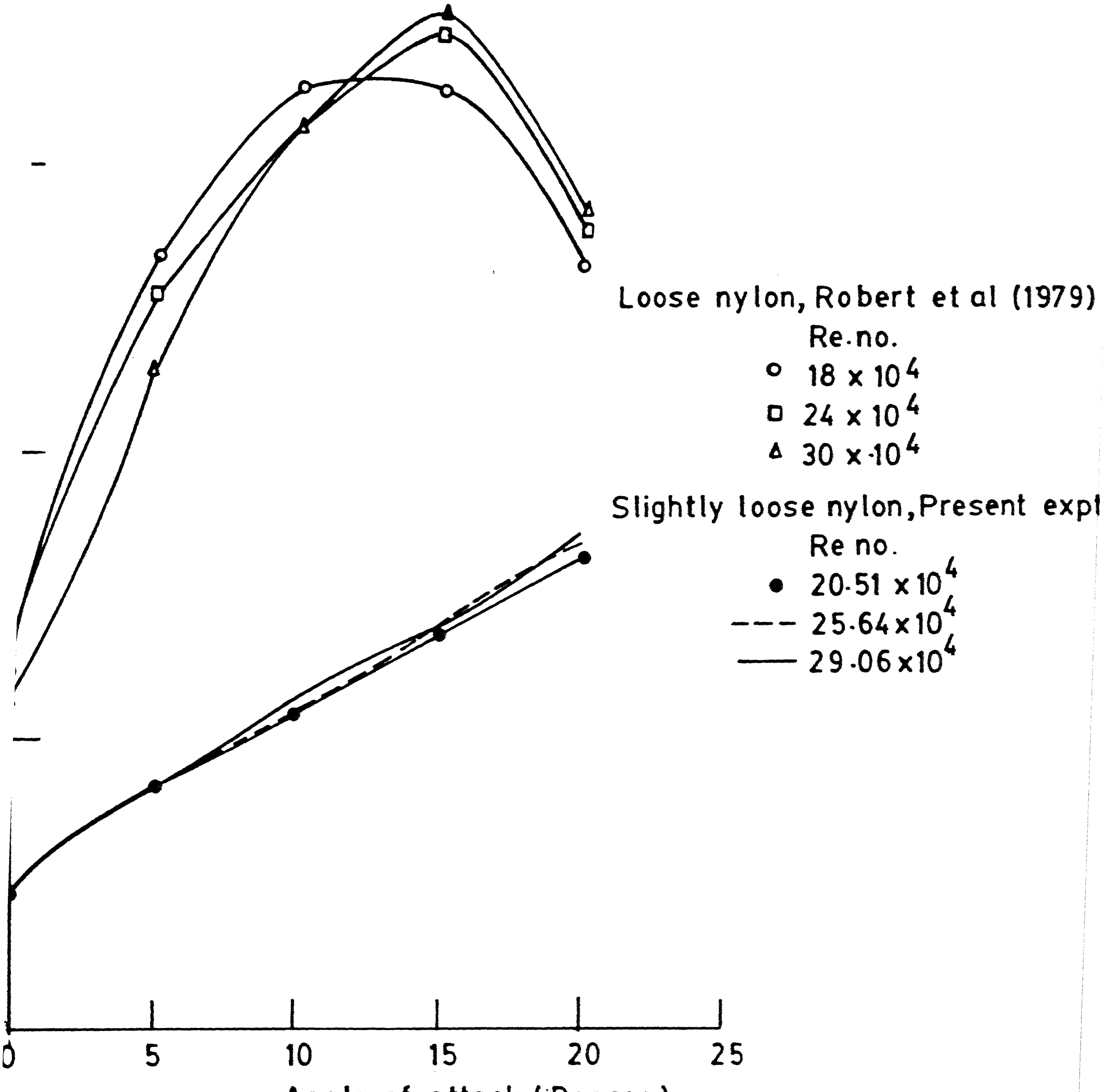
FIG. 26 LIFT COEFFICIENT VS. ANGLE OF ATTACK, LIFT ACTING DOWNWARD



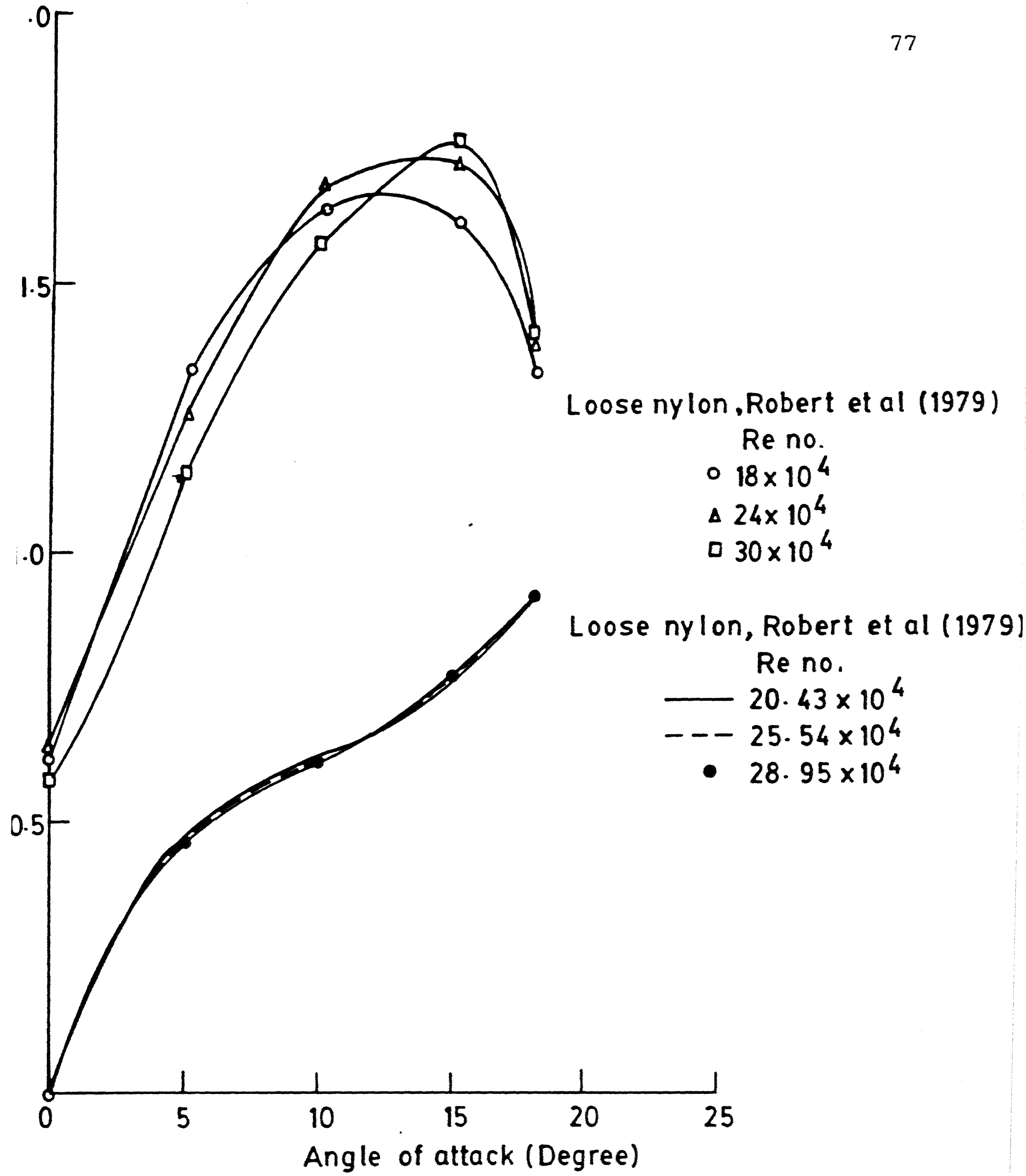
G. 27 LIFT COEFFICIENT VS. ANGLE OF ATTACK, LIFT ACTING DOWNWARD



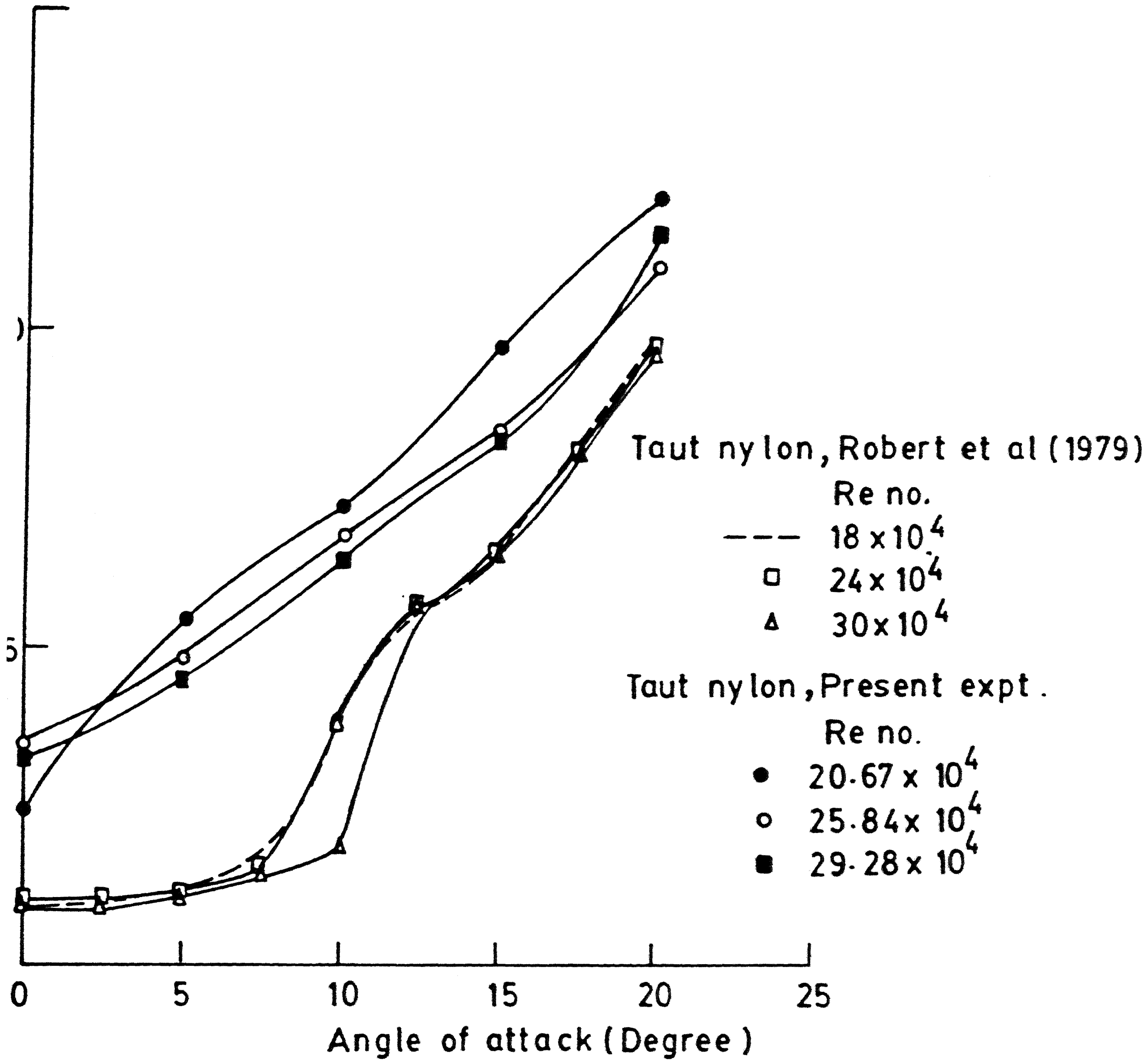
. 29 LIFT COEFFICIENT VS. ANGLE OF ATTACK, LIFT ACTING UP



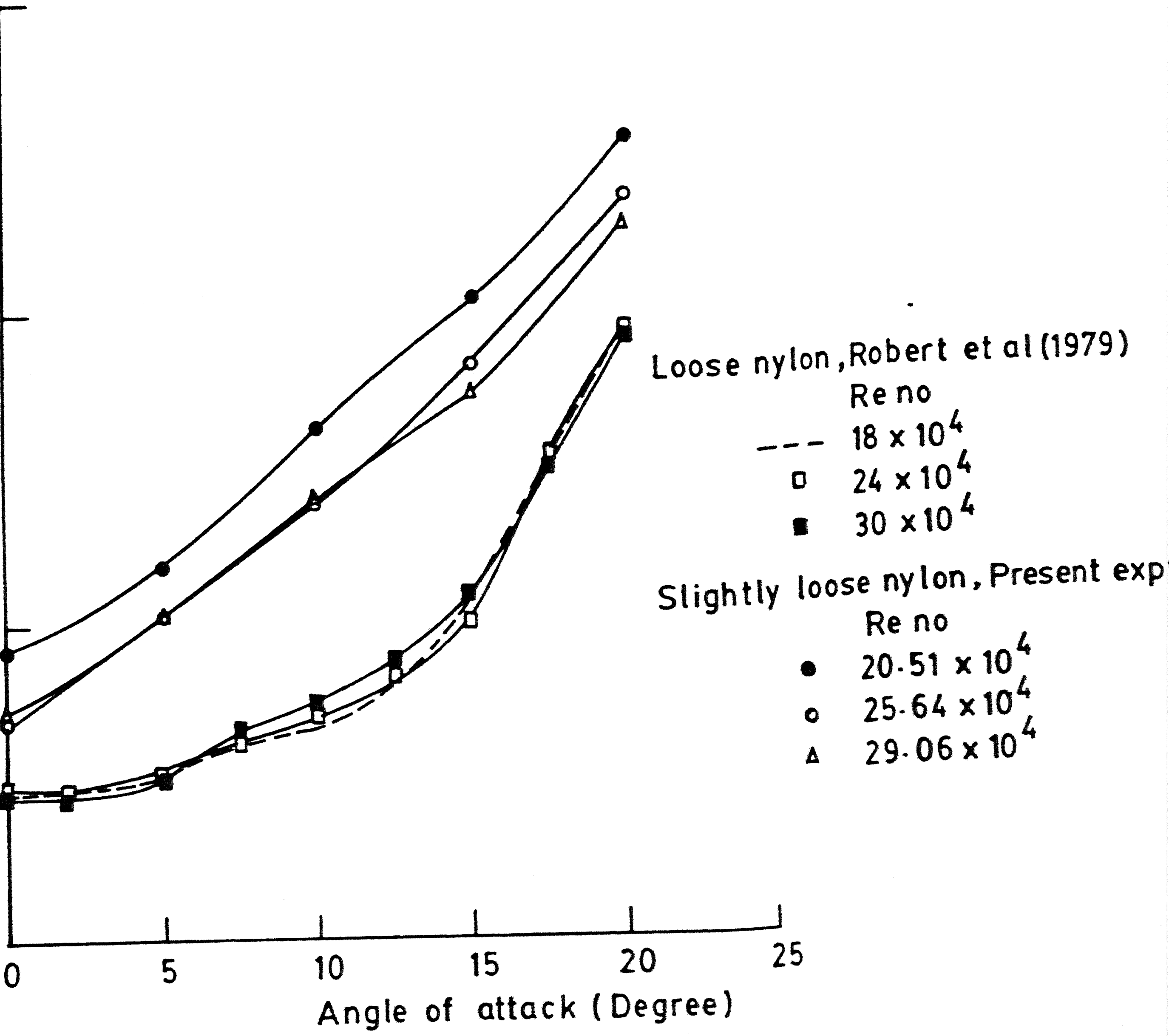
30 LIFT COEFFCIENT VS. ANGLE OF ATTACK, LIFT ACTING UP



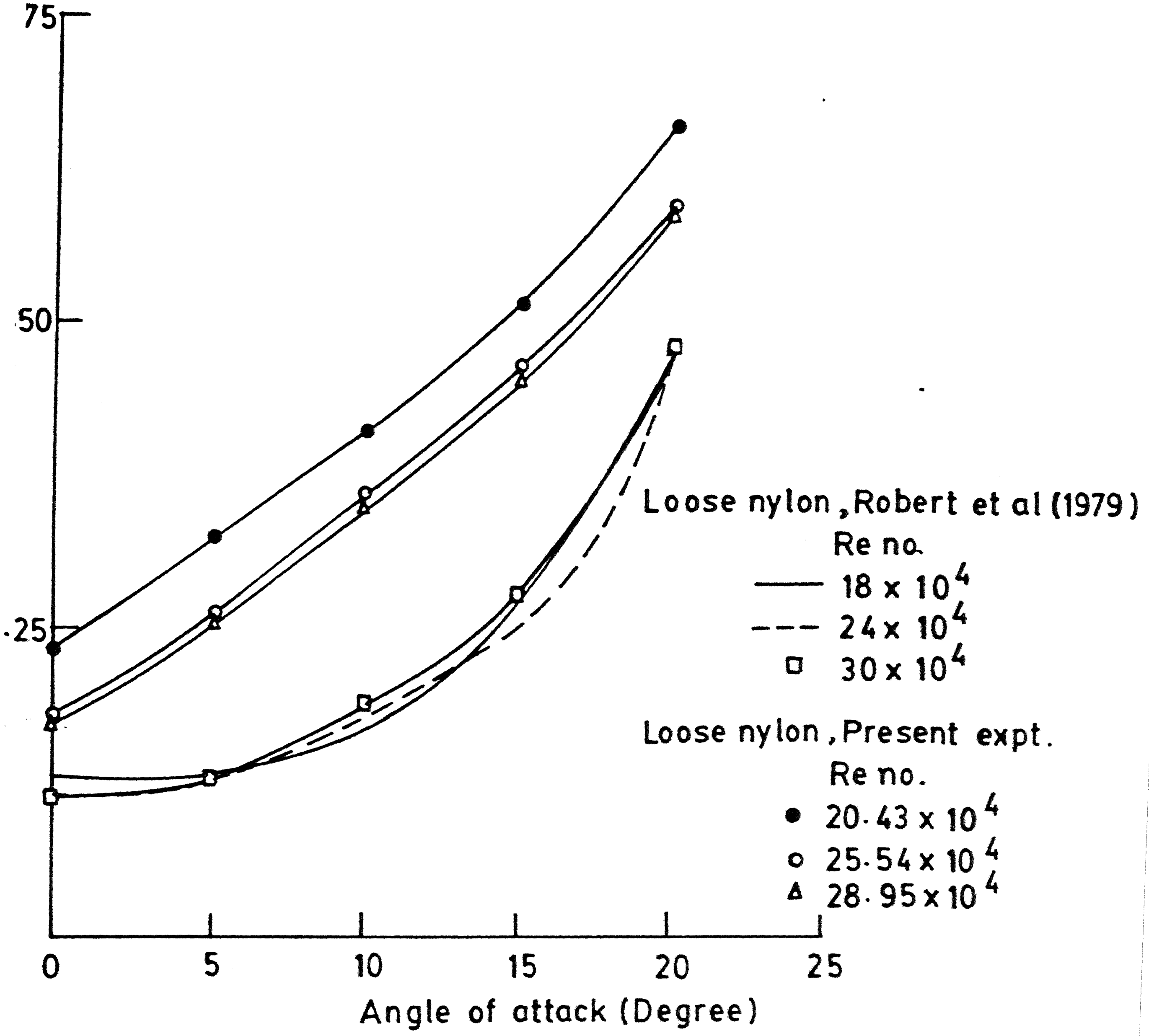
31 LIFT COEFFICIENT VS. ANGLE OF ATTACK, LIFT ACTING UP



32 DRAG COEFFCIENT VS. ANGLE OF ATTACK, WITH LIFT ACTING DOWN



3 DRAG COEFFICIENT VS. ANGLE OF ATTACK, WITH LIFT ACTING DOWN



IG. 34 DRAG COEFFICIENT VS. ANGLE OF ATTACK, LIFT ACTING DOWN

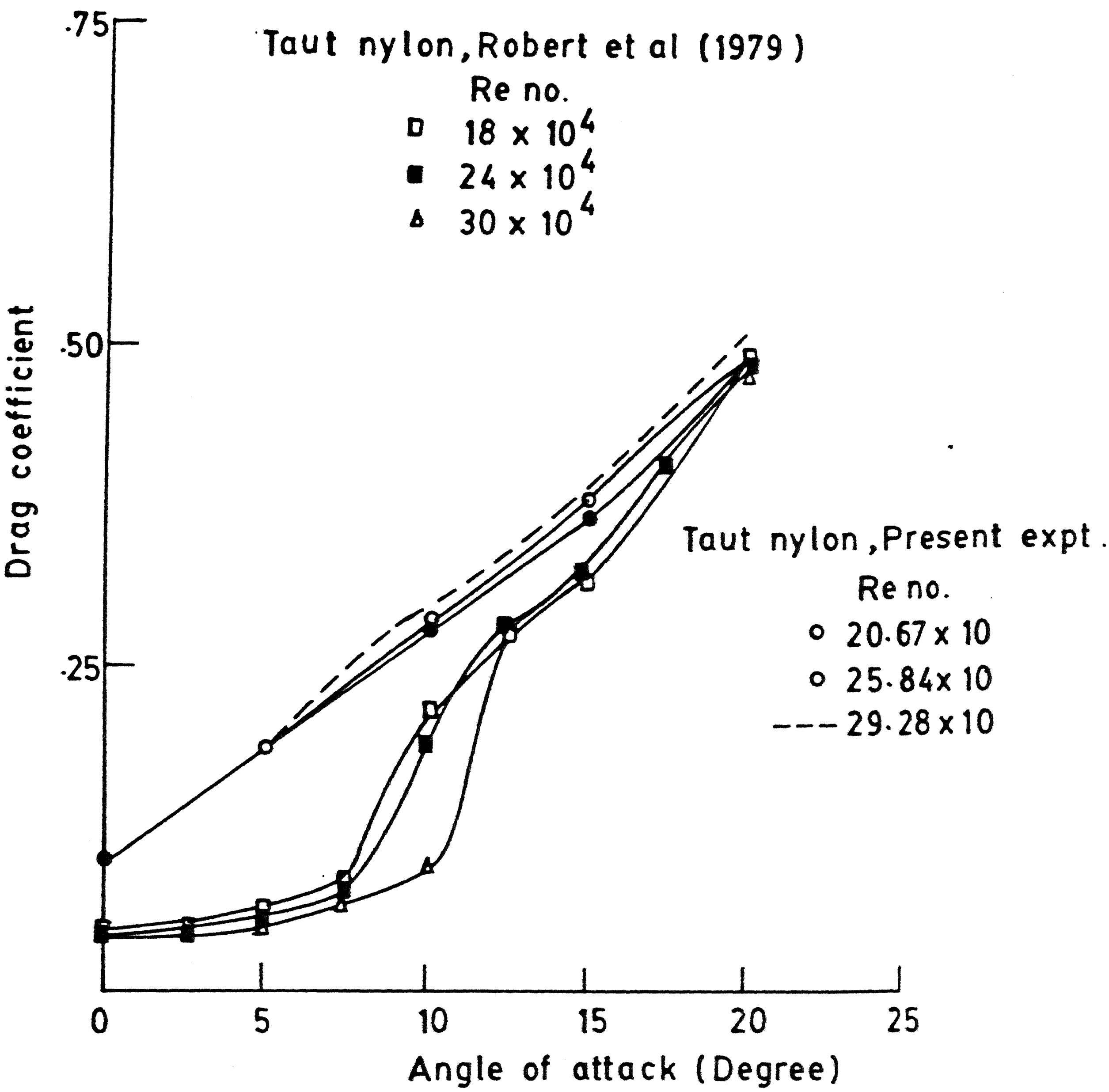


FIG. 35 DRAG COEFFICIENT VS. ANGLE OF ATTACK, WITH LIF ACTING UP

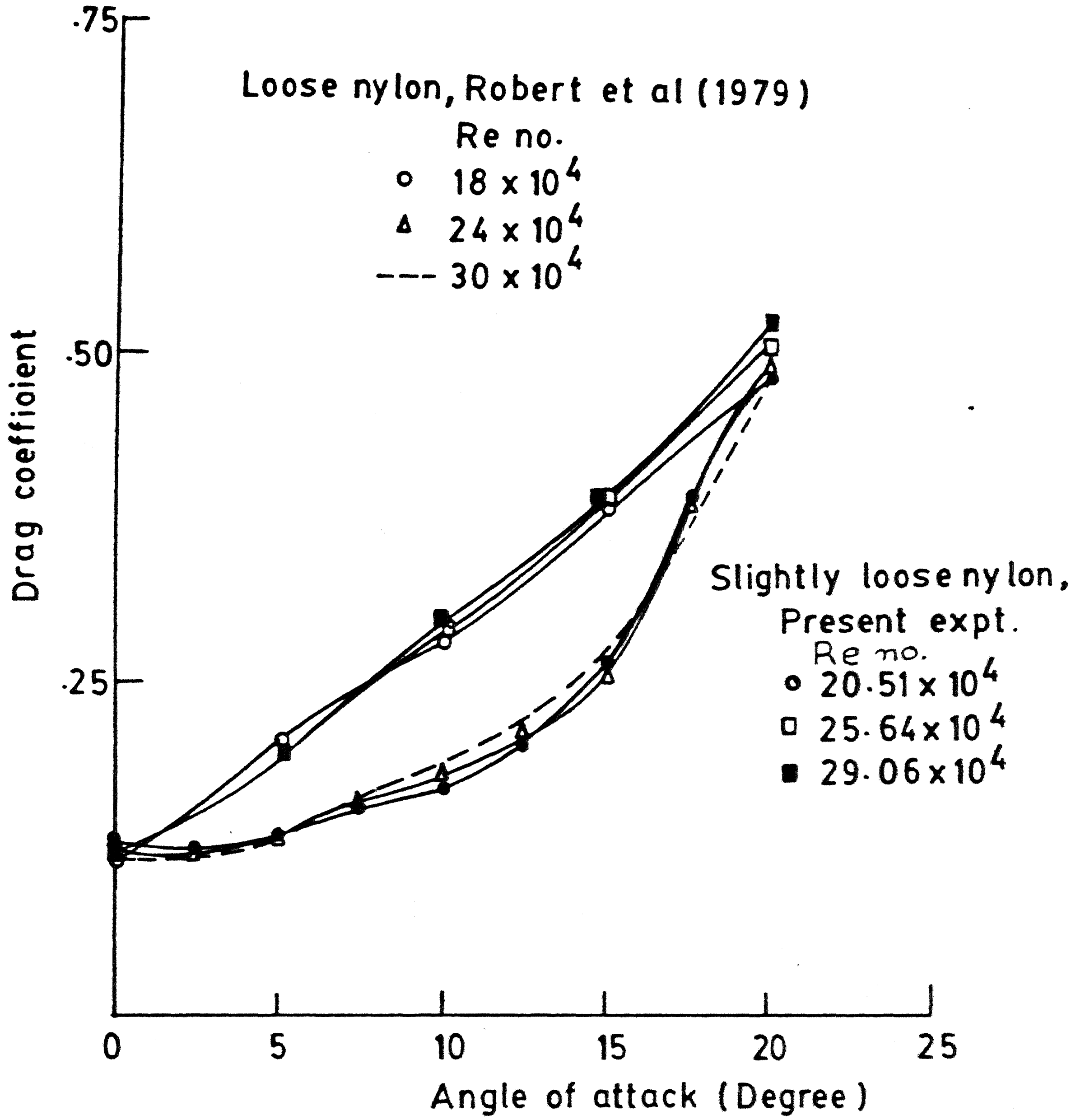


FIG. 36 DRAG COEFFICIENT VS. ANGLE OF ATTACK, WITH L
ACTING UP

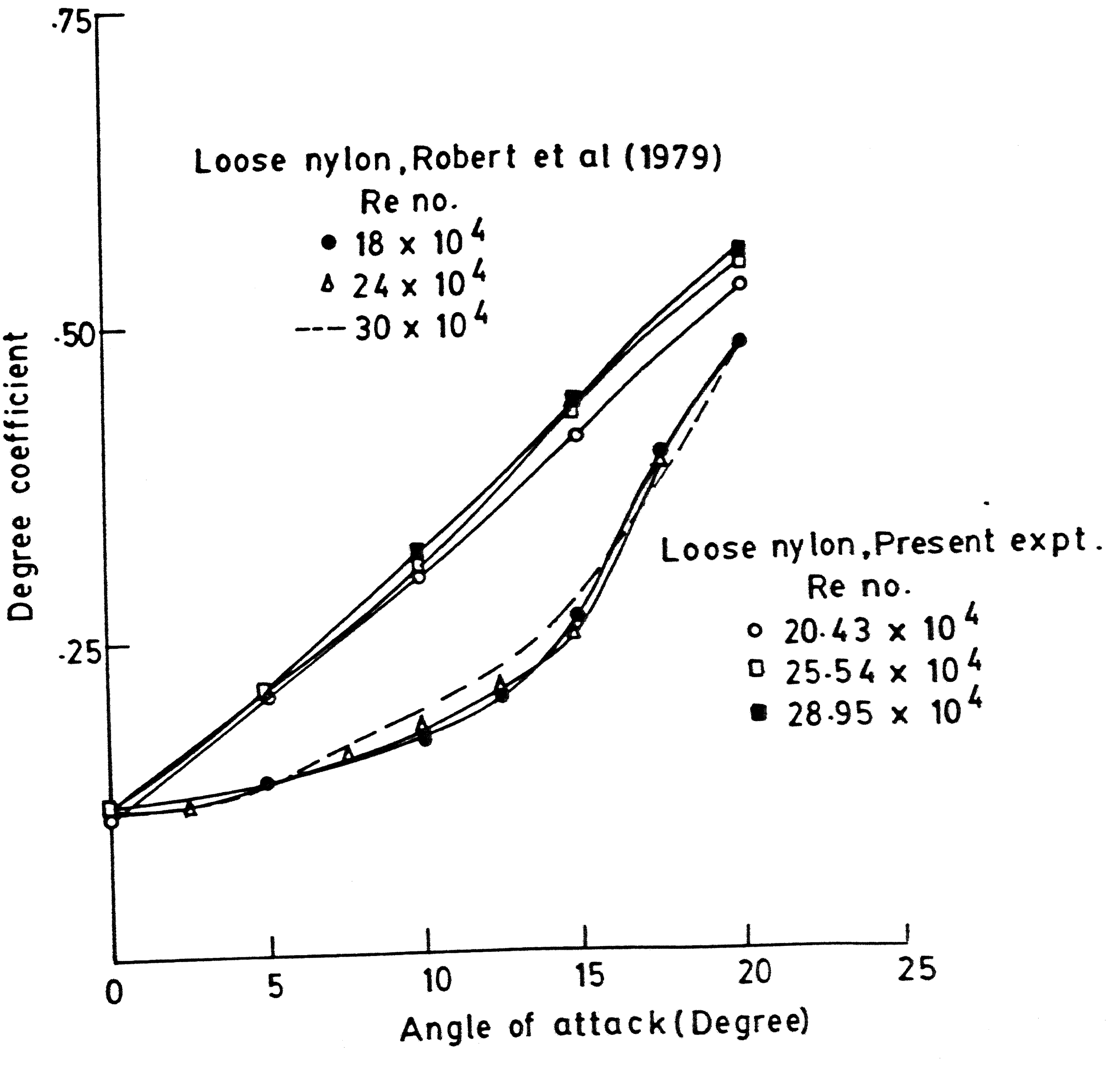


FIG. 37 DRAG COEFFICIENT VS. ANGLE OF ATTACK, WITH LIFT ACTING UP

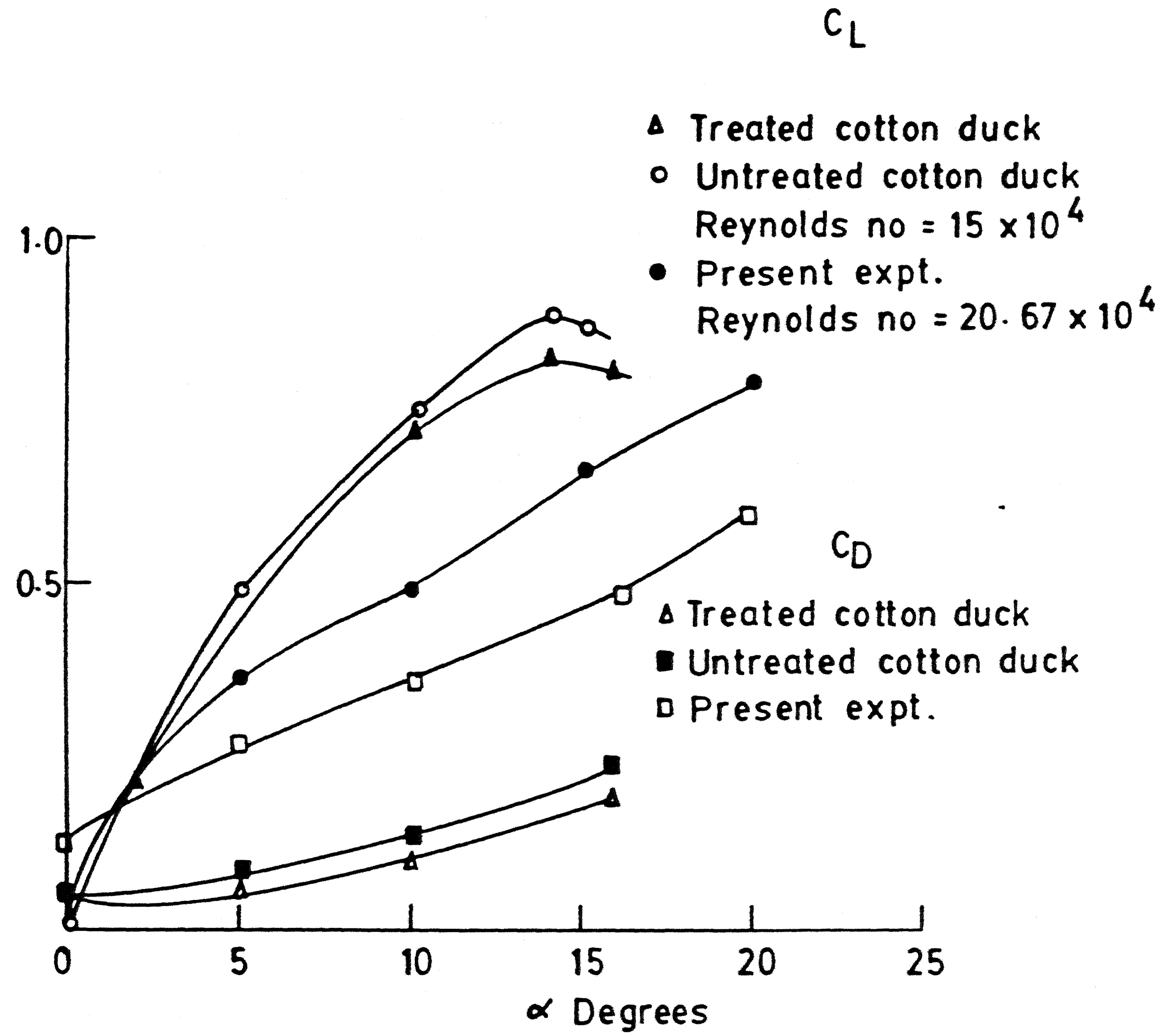
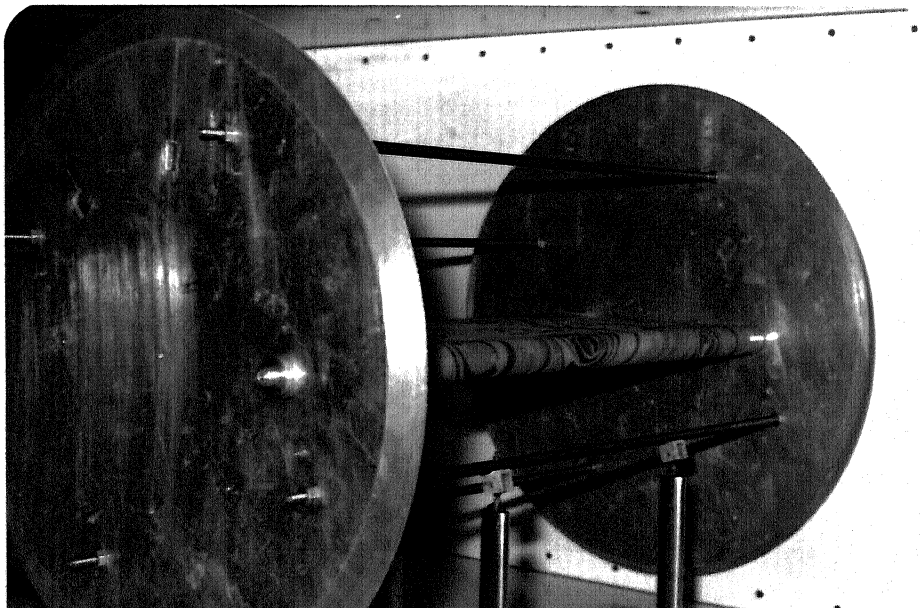
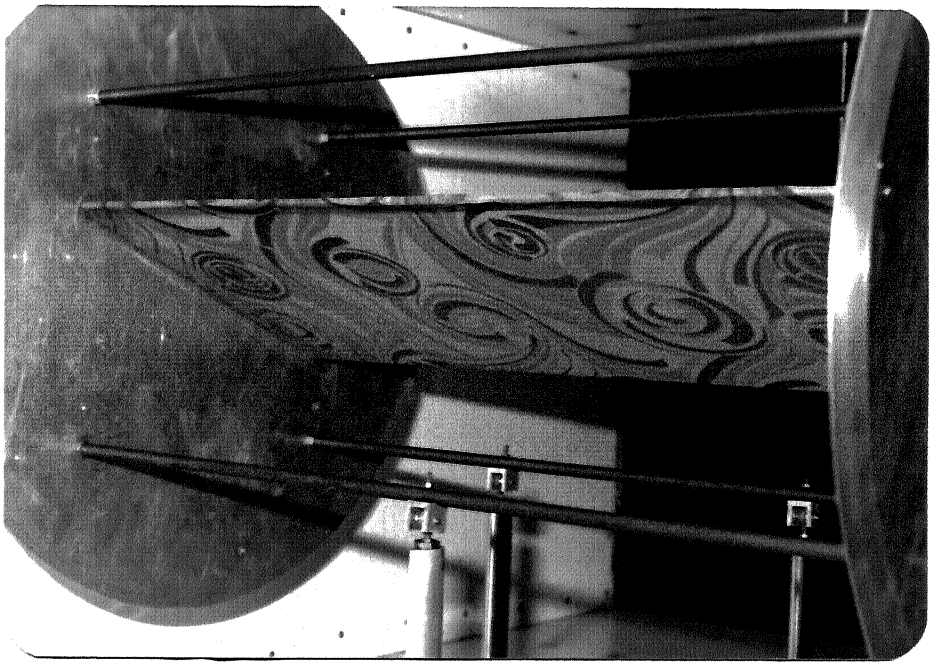


FIG. 38 COMPARISON OF COTTON DUCK SAIL RESULTS OF SWEENEY (1961) WITH PRESENT EXPERIMENTS, LIFT ACTING DOWN

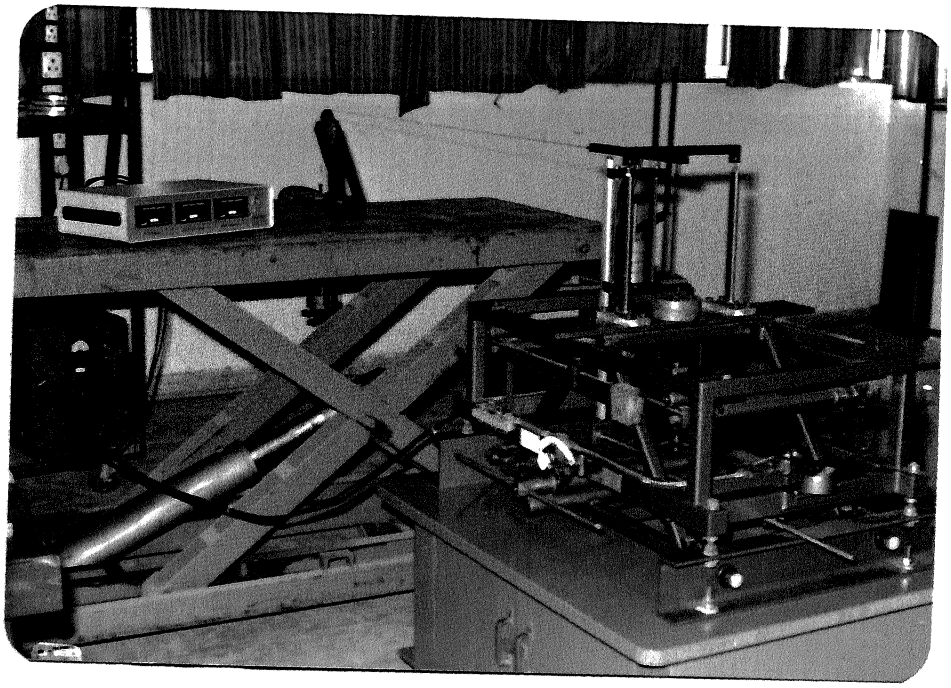
DIFFERENT COMPONENTS OF EXPERIMENTAL SET-UP



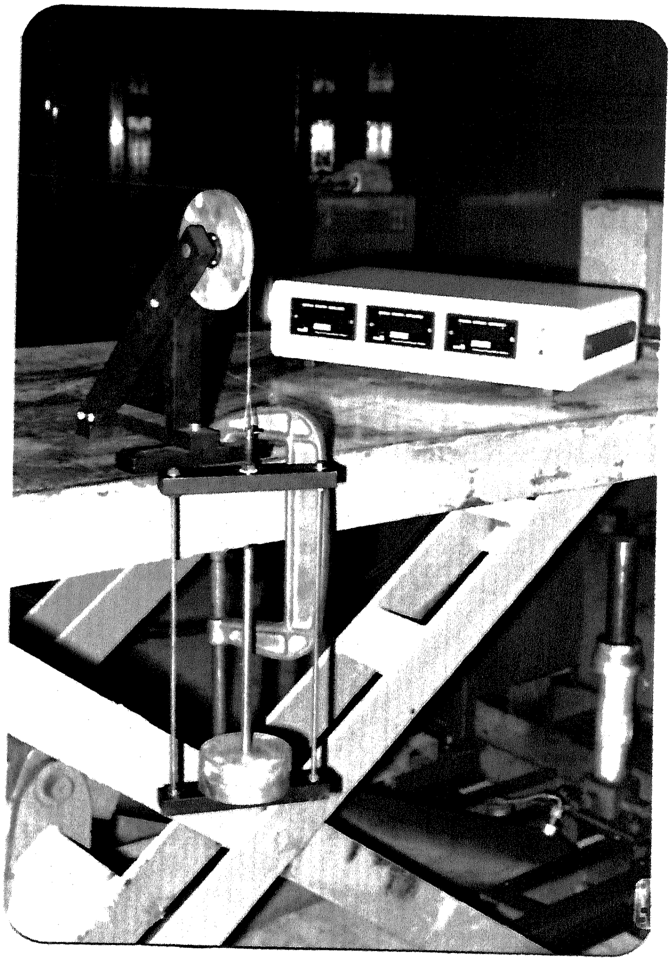
VIEW SHOWING LEADING EDGE OF THE SAIL-AEROFOIL MOUNTED IN BETWEEN TWO CIRCULAR DISCS



CLOSE VIEW OF TRAILING EDGE OF THE SAIL-AEROFOIL



THREE COMPONENT BALANCE WITH THE DIGITAL INDICATOR WHILE CALIBRATING FOR LIFT AND DRAG



PULLY AND WEIGHT SYSTEM USED WHILE CALIBRATING THREE [illegible] BALANCE FOR DRAG